

# Effects of musical experience on children's language and brain development

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## Abstract

The present thesis investigated the maturation of children's neural speech-sound discrimination, its links to behavioral linguistic measures and whether participating music playschool affects these skills. Neural speech-sound discrimination was studied by recording children's (N=75) event-related potentials (ERP) to different speech-sound changes with electroencephalography (EEG), four times in a longitudinal setting starting at the age of 4 to 5. Similarly, children's neurocognitive skills were assessed four times during the 20 months of the follow-up. Children attending music playschool were compared to children partaking in dance lessons or not attending either one of these activities. The results suggest that the 5–6-year-old children's neural speech-sound discrimination reflected by their Mismatch negativity (MMN) responses has an association with phoneme processing skills. Larger MMN amplitudes were found for children scoring higher in *Phoneme processing* test. The intelligence measures were not associated with the brain responses. During the follow-up, children's MMN, P3a and Late discriminative negativity (LDN) responses to phoneme deviations changed, reflecting maturation of auditory change detection. The amplitudes for the MMN response increased and for the LDN decreased for several speech-sound features. Furthermore, the P3a shifted towards adult-like positivity for some sound features. Thus, it seems that even for speech-sounds constantly heard in every-day life of children, the discrimination is still immature at the age of 5–6. The linguistic skills improved more for children partaking in music playschool than for children attending in dance lessons or not participating in either. The magnitude of improvement was dependent on the duration of participation and was evident for phoneme processing skills and vocabulary knowledge. Similar effects did not emerge for perceptual reasoning or inhibition skills. However, music playschool did not modulate children's neural speech-sound discrimination, suggesting that the passively elicited neural modulation associated with the development of linguistic skills are not simplistically linked with the auditory detection of the speech-sound changes. The results highlight the usefulness of change-induced auditory ERPs in indexing i) linguistic skills and ii) maturation of neural auditory discrimination of speech-sounds in childhood, and further demonstrates iii) the beneficial role of structured but playful music sessions for children's linguistic development.

## Tiivistelmä

Väitöskirjassa tutkittiin lasten puheäänten hermostollisen erottelukyvyn kehitystä ja sen yhteyksiä kielellisiin taitoihin, sekä musiikkileikkikouluun osallistumisen vaikutuksia näihin taitoihin. Lasten (N=75) tapahtumasidonnaisia jännitevasteita puheäänimuutoksiin mitattiin aivosähkökäyrämittauksilla (electroencephalografia, EEG) neljään kertaan 20 seurantakuukauden aikana alkaen syksystä, jolloin lapset olivat 4- tai 5-vuotiaita. Lisäksi lapset tekivät neljään kertaan neurokognitiivisia testejä. Osa lapsista osallistui musiikkileikkikouluun, osa tanssitunneille ja osa toimi ns. passiivisina kontrollilapsina. Tulosten mukaan 5–6-vuotiaiden lasten Poikkeavuusnegatiivisuusvasteeseen (Mismatch negativity, MMN) heijastuva hermostollinen puheäänten erottelukyky on yhteydessä äänteiden prosessoinnin taitoihin. Lapsilla, jotka suoriutuivat paremmin äänteiden prosessoinnin testistä, oli suuremmat MMN-vasteet. Ei-kielellistä älykkyyttä mittaavien testien ja tapahtumasidonnaisten jännitevasteiden välillä tätä yhteyttä ei löytynyt. Seurannan aikana äänemuutosten aiheuttamat lasten MMN-, P3a- ja LDN- (Myöhäinen erottelunegatiivisuus, Late discriminative negativity) vasteet muuttuivat, heijastaen kuulohavaintokyvyn kypsymistä. MMN-vaste suureni ja LDN-vaste pieneni usealle puheäännepiirteelle. Lisäksi P3a-vasteen negatiivisuus pieneni ja vaste läheni aikuisille tyypillistä positiivista polariteettia. Näyttääkin siltä, että lasten kuuloerottelukyky kehittyy vielä 5–6-vuoden iässä päivittäin kuultavien puheäänteiden suhteen. Kielelliset kyvyt kehittivät nopeammin lapsilla, jotka osallistuivat musiikkileikkikouluun kuin tanssitunneille osallistuvilla tai passiiviseen vertailuryhmään kuuluvilla lapsilla. Kielellisten taitojen paraneminen näkyi äänteiden prosessointitaitoja ja sanavarastoa mittaavissa testeissä ja oli sidoksissa musiikkileikkikouluun osallistumisen keston. Samanlaisia musiikkileikkikoulun vaikutuksia ei löytynyt ei-kielellistä älykkyyttä ja inhibitiota mittaavista testeistä. Musiikkileikkikoulu ei muokannut seurannan aikana myöskään lasten hermostollista puheäänten kuuloerottelukykyä. Tämä viittaa siihen, että passiivisessa kuuntelutilanteessa syntyneet aiovasteet ja niiden kehitys eivät ole yhteydessä nyt mitattuihin kielellisiin taitoihin itsestään selvällä ja yksinkertaisella tavalla.

Väitöskirjan tulokset korostavat puheäänten muutoksien synnyttämien tapahtumasidonnaisten jännitevasteiden käyttökelpoisuutta i) kielellisten taitojen ja ii) lasten kuuloerottelukyvyn kehityksen selvittämisessä sekä suosittelevat iii) leikillisten ja lapsen kehitystason huomioon ottavan musiikkitoiminnan käyttämistä lasten kielellisen kehityksen tukemiseen.

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Helsinki, 18.12.2018

Tanja Linnavalli



## List of original publications

This thesis is based on the following original publications, which are referred to in the text by Roman numerals (I-III)

- Study I** Linnavalli, T., Putkinen, V., Huotilainen, M., and Tervaniemi, M. (2017). Phoneme processing skills are reflected in children's MMN responses. *Neuropsychologia*, 101, 76–84.
- Study II** Linnavalli, T., Putkinen, V., Huotilainen, M., and Tervaniemi, M. (2018). Maturation of speech-sound ERPs in 5–6-year-old children: A longitudinal study. *Frontiers in Neuroscience*, 12, 814.
- Study III** Linnavalli, T., Putkinen, V., Lipsanen, J., Huotilainen, M., and Tervaniemi, M. (2018). Music playschool enhances children's linguistic skills. *Scientific Reports*, 8(1), 8767.

## Abbreviations

AC	Auditory closure test
EEG	Electroencephalography
ERP	Event-related potential
INH	Inhibition subtest
LDN	Late discriminative negativity
MMN	Mismatch negativity
NEPSY	Neuropsychological battery for investigating children's cognitive profile
PP	Phoneme processing subtest
PRI	Perceptual reasoning index test
SES	Socioeconomic status
VOC	Vocabulary test
WISC	Weschler intelligence scale for children

# 1. Introduction

Linguistic skills are crucial for human beings for both self-expression and connecting with other people. Deficiencies in language-related abilities in childhood may hamper these functions, and also induce difficulties in learning. Knowing how typical linguistic development is manifested in the brain, and what could be done to enhance this maturation, is of essential importance in order to provide facilitating interventions for children with difficulties in language processing.

Well-developed language skills are also crucial for successful functioning in information society. They have a profound effect on mastering school and even for the success in later studies. According to some studies, phonological awareness – a subcategory of phoneme processing ability – is linked to literacy skills and may even predict later reading ability (see Section 1.1). In addition to behavioral linguistic skills, the differences in neural speech-sound discrimination has been found to separate – on group level – children showing typical or atypical linguistic development. Some studies have even found links between neurophysiological measures of speech-sound discrimination and reading skills in typically developing children (see Section 1.3). However, in addition to our limited knowledge of the connections between behavioral and neural indices of linguistic abilities, even the overall picture of maturation of children's neural speech-sound discrimination is far from being complete. The previous studies concerning this maturation are mostly cross-sectional. Furthermore, as the sample sizes have been mostly moderate, and the compared groups have typically included children across age-range of 2–3 years, the present literature is unable to provide a conclusive picture of auditory maturation (see Section 1.2).

Investigating auditory event-related potentials (ERPs) offers a comparatively easy method to focus on auditory processing. The method is safe, affordable and non-invasive, and well-suited for studying children. Particularly change-induced ERPs, such as the mismatch negativity (MMN), the P3a, and the Late Discriminative Negativity (LDN) provide a perspective on language development, beyond behavioral measures. Taken together, these responses reflect multiple stages of information processing, and as they can be elicited in passive conditions, they offer an applicable method to investigate children or, e.g., clinical groups.

Several studies have supported the notion of music training enhancing children's linguistic development and maturation of neural speech-sound discrimination (see section 1.4). However,

most of the studies have employed extensive music interventions taking several hours weekly, not feasible in every-day life of families, kindergartens and schools. If – as it seems – music interventions could improve linguistic development – it is important to know how extensive training is needed. The more feasible an effective intervention is, the more likely it is to be included in children's daily curricula.

### **1.1. Development of neural speech-sound discrimination and phonological awareness**

For adults, listening to their native language is an effortless act, but actually it is a result of development and constant practise throughout the early years of childhood. As infants, human beings are capable of discriminating speech-sounds in a universal fashion. During the first months of life all speech sound contrasts are processed in a similar way. Owing to social interaction with the caregiver(s), specialization for native language contrasts enhances and before the age of one, typically developing children cease to differentiate successfully foreign language phonemes (Kuhl, Conboy, Coffey-Corina, Padden, Rivera-Gaxiola & Nelson, 2008; see Kuhl, 2004).

As will be discussed in more detail in the following sections, based on ERP studies children discriminate changes in frequency, intensity, sound duration and phoneme features even passively, that is, while they perform another task such as watching a muted movie (for a review, Lovio, 2013; Putkinen, 2014; Kuuluvainen, 2016). However, this discrimination differs from that of adults' and it is not known when this discrimination ability reaches adult levels in typically developing children. In addition, there is evidence suggesting that linguistically atypically developing children show differences in indices of neural speech-sound discrimination when compared with typically developing children (Lovio, Nääätänen & Kujala, 2010; Hämäläinen, Guttorm, Richardson, Alku, Lyytinen & Leppänen, 2013; Frey, François, Chobert, Besson & Ziegler, 2018).

Phoneme processing refers to the ability of processing the sounds of native language, and it is thought to consist of three components: *phonological memory*, *phonological access to lexical storage* and *phonological awareness* (Anthony & Francis, 2005). Out of these subcomponents, phonological awareness – an ability to recognize and manipulate the sound structure of native

language – seems to be most strongly related to literacy skills (Anthony & Francis, 2005; Ziegler & Goswami, 2005). Phonological awareness (PA) matures throughout childhood, and it is thought to develop from perception of larger units (i.e., syllables) to perception of smaller units (i.e., phonemes) (Carroll, Snowling, Stevenson & Hulme, 2003; Anthony & Francis, 2005; Silvén, Poskiparta, Niemi & Voeten, 2007), improving and stabilizing throughout the childhood (Suortti & Lipponen, 2014; Lonigan, Burgess, Anthony & Barker, 1998). Already 2-year-olds are capable of performing tasks requiring phonological awareness, e.g., recognizing phoneme structures (Suortti & Lipponen, 2014). By the age of 5 to 6, most children seem to manage tasks requiring, e.g., rhyme detection and production and manipulation of syllables and phonemes (Suortti & Lipponen, 2014; Lonigan et al., 1998). Phonological awareness in early childhood seems to predict later reading skills (Kirby, Parrila & Pfeiffer, 2003; Silvén, Poskiparta & Niemi, 2004; MacDonald & Cornwall, 1995; Anthony & Francis, 2005) and additionally, differences in performance in PA seem to have an association with reading skills in elementary school children (Savage, Frederickson, Goodwin, Patni, Smith & Tuersley, 2005). However, it is not clear if superior reading skills result from superior phonological awareness – or vice versa – or is the link only correlational (see Castles & Coltheart, 2004; Melby-Lervåg, Lyster, & Hulme, 2012; National Institute for Literacy, 2008; Hatcher, Hulme & Snowling, 2004; see also Korkman, Barron-Linnankoski & Lahti-Nuuttila, 1999; Sodoro, Allinder & Rankin-Erickson, 2002).

## **1.2. Maturation of auditory discrimination as indexed by event-related potentials**

Auditory event-related potentials (ERP) are an important tool to investigate auditory cognition and its development. Measuring ERPs can bring us useful information about auditory discrimination beyond behavioral measures, and this is especially convenient with, e.g., children and medical groups that are not capable of concentrating or staying still long enough to produce the needed amount of data. Some components – such as mismatch negativity (MMN) – are known to be evident already in newborn infants, while our knowledge of the emergence of others (e.g., P3a and LDN) is scarce and even contradictory. Furthermore, the features of the responses, e.g., the polarities or latencies seem to vary substantially between children. For instance, a negative component occurring after 300 ms could be a late MMN or an early LDN,

depending on the earlier response. There are likely to be many simultaneously ongoing neural processes in the brain and this further complicates the interpretation of children's responses. The neural mechanism behind the maturation of ERPs is likely partly determined by the increase of axon myelination increasing the conduction velocity and changes in synaptic density (Huttenlocher & Dabholkar, 1997; Moore & Guan, 2001; Brody, Kinney, Kloman & Gilles, 1998).

Most studies investigating the maturation of auditory event-related responses in children are cross-sectional comparisons of groups comprised of younger and older children, with modest number of participants (Shafer, Morr, Kreuzer & Kurtzberg, 2000; Shafer, Yu & Datta, 2010; Gomot, Giard, Roux, Barthélémy & Bruneau, 2000; Lee et al., 2012; Bishop, Hardiman & Barry, 2011; Wetzel, Widmann, Berti & Schröger, 2006; Gumenyuk, Korzyukov, Alho, Escera & Näätänen, 2004; Kihara, Hogan, Newton, Garrashi, Neville & de Haan, 2010; Hommet, Vidal, Roux, Blanc, Barthez & De Becque, 2009; Liu, Chen & Tsao, 2014; Hong, Shuai, Frost, Landi, Pugh & Shu, 2018). The results of these studies have been contradictory, some finding differences between age groups for inspected components (Lee et al., 2012; Bishop et al., 2011; Wetzel et al., 2006; Gumenyuk et al., 2004; Kihara et al., 2010; Hommet et al., 2009; Liu et al., 2014; Hong et al., 2018) and some not (Shafer et al., 2000; 2010; Gomot et al., 2000; Ruhnau, Wetzel, Widmann & Schröger, 2010; Ruhnau, Herrmann, Maess, Brauer, Friederici & Schröger, 2013). The investigated responses in these studies have been elicited by frequency changes (Shafer et al., 2000; Gomot et al., 2000; Bishop et al., 2011; Wetzel et al., 2006), phonemic stimuli – e.g., vowel or consonant change – (Shafer et al., 2010; Lee et al., 2012; Bishop et al., 2011; Liu et al., 2014; Hommet et al., 2009; Hong et al., 2018) and novel sounds (Gumenyuk et al., 2004; Kihara et al., 2010).

### **1.2.1. Mismatch negativity as an index of auditory change detection**

The mismatch negativity (MMN) is a component elicited typically between 100–250 ms from stimulus onset by an infrequent sound in the stream of repeating stimuli (Näätänen, 1992). Several theories have been suggested for explaining the functional significance of the response. Two hypotheses that dominate the field are the *model adjustment hypothesis* and the *adaptation hypothesis*. The *model adjustment hypothesis* holds that the MMN response is an index of a

violation of regularity in a structured auditory stream (Näätänen, 1992; Näätänen and Winkler, 1999; Näätänen, Paavilainen, Rinne & Alho, 2007) or a mismatch between the predicted and perceived acoustic input (Winkler, Denham, & Nelken, 2009; see, e.g., Baldeweg, 2007; but this suggestion remains controversial). In other words, MMN results from the comparison between the incoming sound and the prediction made based on previous sound stream. Instead, *neuronal adaptation* theory suggests that the elicitation of the MMN is due to neurons reacting to new sound features causing an increase in potential (see, e.g., Jääskeläinen et al., 2004; Nelken & Ulanovsky, 2007 and May & Tiitinen, 2010). In other words, local neuronal populations adapt to incoming sounds and become less responsive to them. According to this theory, “new” sound activates new neurons, specific to different sound features and this is seen as an increase in amplitude in MMN latency range. However, there is considerable amount of experimental evidence arguing against the neuronal adaptation hypothesis (Winkler, Tervaniemi & Näätänen, 1997; Atienza and Cantero, 2001; Yabe, Tervaniemi, Reinikainen & Näätänen, 1997) and thus, it is deemed controversial (see review, Näätänen, Jacobsen, & Winkler, 2005; Näätänen, Kujala, & Winkler, 2011). It has also been suggested that these two theories could be combined as one, in *predictive coding* framework. This framework covers both *model adjustment* and *neuronal adaptation* hypotheses by positing that the brain uses a generative model of current stimulus train to infer the sensory input and then uses precision-weighted prediction errors to constantly update the model (Garrido, Kilner, Stephan & Friston, 2009; Stefanics, Horváth & Stephan, 2018).

The MMN seems to have two separate neural sources that are typically assumed to contribute to different functions (Giard, Perrin, Pernier, & Bouchet, 1990). The supratemporal planes of the auditory cortices (Näätänen & Escera, 2000; Rinne, Alho, Ilmoniemi, Virtanen, & Näätänen, 2000; Kropotov, Näätänen, Sevostianov, Alho, Reinikainen & Kropotova, 1995; Kropotov et al., 2000; Alho et al., 1996; Levänen, Ahonen, Hari, McEvoy, & Sams, 1996; Tervaniemi et al., 2000; Opitz, Rinne, Mecklinger, von Cramon, & Schröger, 2002) are presumed to reflect memory functions by comparing and predicting incoming sounds. Instead, the prefrontal cortex (Näätänen & Escera, 2000; Rinne et al., 2000; Alho, Woods, Algazi, Knight, & Näätänen, 1994; Doeller, Opitz, Mecklinger, Krick, Reith & Schröger, 2003; Giard et al., 1990; Marco-Pallares, Grau, & Ruffini, 2005; Schönwiesner, Novitski, Pakarinen, Carlson, Tervaniemi & Näätänen, 2007) is thought to execute the involuntary attentional allocation towards the stimulus (Näätänen et al., 2007; for a critical discussion, see Deouell, 2007). Children seem to have

more central scalp distribution of MMN than adults (Gomot et al., 2000; Shafer et al., 2010). It has been suggested that the structural maturation of cerebral cortex progresses from primary sensory and motor regions towards the regions associated with higher-order cognitive functions (Lenroot & Giedd, 2006; Gogtay & Thompson, 2010), and this might possibly be reflected in the differential MMN scalp distribution between adults and children.

Traditionally, the MMN was recorded in an oddball paradigm with a sound or sounds that differ from the continuously repeated standard sound in one feature, e.g. frequency (Morr, Shafer, Kreuzer & Kurtzberg, 2002). Later, this paradigm has been developed into a multifeature paradigm (Näätänen, Pakarinen, Rinne & Takegata, 2004) with several alternating deviants, each differing from the standard stimulus in only one feature and acting as standards to each other. The sounds are presented in stream, with every other sound being a standard and every other a(n) (alternating) deviant, an arrangement that allows considerably faster data collection than the oddball paradigm. Empirically, multifeature paradigm has been found to elicit responses corresponding to those seen in experimental settings with oddball paradigm in adults (Näätänen et al., 2004; Pakarinen, Lovio, Huotilainen, Alku, Näätänen & Kujala, 2009; Kujala, Lovio, Lepistö, Laasonen & Näätänen, 2006) and children (Lovio, Pakarinen, Huotilainen, Alku, Silvennoinen & Näätänen, 2009; Partanen, Pakarinen, Kujala & Huotilainen, 2013b).

The MMN is elicited also in passive conditions and thus, this response component is well-suited for investigating children (Näätänen, Astikainen, Ruusuvirta & Huotilainen, 2010; for a review, see, e.g. Näätänen et al., 2007). The MMN is reliably established in pre-schoolers (Lovio et al., 2009; Lee et al., 2012) and in school children (Cheour, Leppänen & Kraus, 2000; Datta, Shafer, Morr, Kurtzberg & Schwartz., 2010; Kraus, Koch, McGee, Nicol & Cunningham, 1999), and even fetuses (Huotilainen et al., 2005) and newborn infants show MMN-like responses (Cheour et al., 2000; Kushnerenko, Čeponienė, Balan, Fellman & Näätänen, 2002a; Partanen, Kujala, Tervaniemi, and Huotilainen, 2013a; Trainor, Samuel, Desjardins & Sonnadara, 2001), e.g., for frequency changes (Alho, Sainio, Sajaniemi, Reinikainen & Näätänen, 1990), speech stimuli (Csépe, 1995), musical stimuli (Partanen et al., 2013a) and emotional pseudo-word stimuli (Kostilainen et al., 2018). In 3–12-year-old children, the MMN response has been recorded for deviations in frequency (Shafer et al., 2000; Maurer, Bucher, Brem & Brandeis, 2003a), intensity (Lovio et al., 2009; 2010; Partanen et al., 2013b), phonemes (Čeponienė, Lepistö, Soininen, Aronen, Alku & Näätänen, 2004; Datta et al., 2010; Kraus et al., 1999; Kuuluvainen, Leminen & Kujala, 2016; Lovio et al., 2009; 2010), and vowel duration (Lovio et al., 2009;



2010). Even abstract changes, like sound pairs with varying direction of frequency differences have elicited MMN in children (Gumenyuk, Korzyukov, Alho, Winkler, Paavilainen & Näätänen, 2003).

The accuracy of behavioral discrimination is reflected in the amplitude and the latency of the MMN component (Amenedo & Escera, 2000; Kujala, Kallio, Tervaniemi, & Näätänen, 2001; Novitski, Tervaniemi, Huotilainen, & Näätänen, 2004; Näätänen, Schröger, Karakas, Tervaniemi, & Paavilainen, 1993; Tiitinen, May, Reinikainen, & Näätänen, 1994) – the more precise the change detection is, the larger the amplitude and shorter the latency of the response – and this makes it an attractive tool to investigate the maturation of auditory discrimination. In preschool and early school-age, the MMN amplitudes are reported to be small for subtle acoustic changes (Lovio et al., 2009; see e.g. Cheour et al., 2000). However, the studies looking at the differences in MMN amplitudes between different ages are somewhat conflicting. In some studies, no MMN amplitude differences between children of different ages or children and adults have been found for frequency or vowel changes (Shafer et al., 2010; 2000; Gomot et al., 2000; Bishop, Hardiman & Barry, 2010), whereas other studies have reported finding MMN amplitudes to be larger in older than younger children or in adults compared to children (Lee et al., 2012; Bishop et al., 2011; Wetzel & Schröger, 2007b; Wetzel et al., 2006; Wetzel, Widmann & Schröger, 2011; Partanen, Torppa, Pykäläinen, Kujala, & Huotilainen, 2013c). However, the differences in the MMN seem to be specific to the deviant type. According to one study (Partanen et al., 2013c), older children showed larger responses to vowel deviants but smaller responses to frequency deviants compared to younger children. The maturation of MMN is supposed to continue at least until adolescence (Bishop et al., 2011; Wetzel & Schröger, 2007b), but it is not known when this response component reaches the adult magnitude and latency, and further, if the maturation happens linearly.

In addition to maturation, also auditory exposure and expertise seem to modulate the MMN. For instance, linguistic (Shestakova, Huotilainen, Čeponiene & Cheour, 2003; Näätänen, 2001) or musical learning (e.g., Putkinen, Tervaniemi, Saarikivi, Ojala & Huotilainen, 2014; Chobert, Francois, Velay & Besson, 2014) have been reported to enhance MMN amplitudes in connection with speech or musical stimuli (see below).

The overview of previously published results reveals the difficulties in forming a coherent picture of the MMN maturation: the paradigms are different, the saliency of changes in different

deviant types are not comparable (e.g., vowel change vs. consonant change), the age-groups are mostly composed of children from wide age-range and the number of participants is generally modest, considering the large amount of variance that children's responses typically show.

### **1.2.2. P3a as an indicator of auditory attention in children**

After a salient deviant or a novel sound, the MMN is often followed by a fronto-centrally maximal positive peak with latency around 200–400 ms from stimulus onset, referred to as the P3a response (Squires, Squires, & Hillyard, 1975). It seems that novel or very salient distractors elicit larger P3a responses than the more subtle ones (Yago, Corral & Escera, 2001; Berti, Roeber & Schröger, 2004; Escera, Alho, Winkler & Näätänen, 1998; Wetzel et al., 2006; Wronka, Kaiser & Coenen, 2012). As a consequence, it is commonly proposed that P3a reflects involuntary attentional switch towards the distractor sound (Escera, Alho, Schröger, & Winkler, 2000; Escera & Corral, 2007; Friedman, Cycowicz, & Gaeta, 2001; Linden, 2005; Polich, 2007), an interpretation that is further supported by results showing increased reaction times during behavioral task for task-irrelevant deviating or novel sound (Escera et al., 1998; Gumenyuk et al., 2004; Wetzel et al., 2006; Berti, Grunwald & Schröger, 2013; Wetzel et al., 2007a). Nevertheless, it is not clear whether the reaction time is correlated with the magnitude of P3a amplitude (cf. Ramchurn, de Fockert, Mason, Darling & Bunce, 2014 and Berti et al., 2013).

The P3a seems to originate from several brain regions. Several studies have found evidence for the involvement of frontal sources in the emergence of the P3a (epileptic patients Alain, Richer, Achim, & Saint Hilaire, 1989; Baudena, Halgren, Heit, & Clarke, 1995; Knight, 1996; Mecklinger & Ullsperger, 1995; Knight, 1984; Løvstad et al., 2012; Volpe, Mucci, Bucci, Merlotti, Galderisi & Maj, 2007; Schröger, Giard, & Wolff, 2000). In addition, elicitation of the P3a appears to involve auditory cortex (Alho et al., 1998; Yago, Escera, Alho, Giard & Serra-Grabulosa, 2003), anterior cingulate gyrus (Wronka et al., 2012), hippocampus (Knight, 1996) and parahippocampal gyri (Knight, Scabini, Woods et al. 1989) (for reviews, see Huang, Chen & Zhang, 2015; Escera et al., 2000).

Already infants show a positive component similar to adult P3a to large deviants (Håden, Stefanics, Vestergaard, Denham, Sziller & Winkler, 2009; Kushnerenko, Ceponiene, Balan, Fellman, Huotilainen & Näätänen, 2002b; Kushnerenko et al., 2007), and a similar response

has also been found for salient distractors in toddlers (Putkinen, Niinikuru, Lipsanen, Tervaniemi & Huotilainen, 2012) and even for subtle vowel changes in kindergarten children (Shestakova et al., 2003). Topographically, the P3a seems to have more anterior distribution in younger children and shift towards more central and parietal distribution with age (Cycowicz, Friedman & Rothstein, 1996; Ruhnau et al., 2010; 2013; Wetzel et al., 2011). Furthermore, the latency of the response seems to decrease between childhood and adolescence (Fuchigami et al., 1995; Cycowicz, et al., 1996).

As the P3a seems to reflect the magnitude of distraction (Yago et al., 2001; Berti et al., 2004; Escera et al., 1998; Wetzel et al., 2006; Wronka et al., 2012) and as the common interpretation is that children are more easily distracted than adults (see, e.g., Wetzel et al., 2006; Gumenyuk et al., 2004), it is natural to assume that the children show larger P3a responses than adults. The assumption that this response decreases with age in childhood is supported by studies comparing responses elicited by novel sounds, presented to children and adults (Wetzel et al., 2011; Määttä, Saavalainen, Könönen, Pääkkönen, Muraja-Murro & Partanen, 2005) or younger and older children (Gumenyuk, 2004; Cycowicz et al., 1996; Wetzel & Schröger, 2007b). However, there are also studies not finding any differences between age groups for novel sounds (Ruhnau et al., 2010; 2013; Gumenyuk et al., 2001) and some even reporting larger P3a amplitudes in older children or adults (Kihara et al., 2010; Cycowicz & Friedman, 1997) compared to younger participants.

The evidence of the maturation of the P3a response for less salient sound changes is conflicting: whereas some studies have found no differences between age groups (Wetzel & Schröger, 2007a; Wetzel & Schröger, 2007b; Čeponienė et al., 2004), one study showed results suggesting the P3a decreased with age (Wetzel et al., 2006). Furthermore, by visually inspecting the response waves in some studies, one may argue that the P3a amplitude for deviating stimuli actually increases with age (Horváth, Czigler, Birkás, Winkler, & Gervai, 2009), at least in childhood (Gomot et al., 2000; Shafer et al., 2000).

In any case, the results suggest that the developmental trajectory of the P3a response depends on the magnitude of the change in stimuli. For very distracting sounds – such as novels – the maturation means more efficient suppressing of the involuntary attention to irrelevant distracting sounds, manifested in a decreasing P3a amplitude. In contrast, for less distracting changes in sounds – e.g., small frequency or phoneme deviations – the threshold for discrimination seems

to decrease, reflecting more efficient auditory detection manifested in the increase of P3a amplitude with age.

### **1.2.3. Late discriminative negativity**

Late discriminative negativity, LDN (Korpilahti, Lang & Aaltonen, 1995), is a frontally maximal negative response occurring typically 350–550 ms after stimulus onset (Korpilahti et al., 1995; Bishop et al., 2011; Čeponienė, Cheour & Näätänen, 1998; Draganova, Eswaran, Murphy, Huotilainen, Lowery, & Preissl, 2005; Kushnerenko et al., 2002a), although it has been reported to be found also on later latency ranges (Ervast, Hämäläinen, Zachau, Lohvansuu, Heinänen & Veijola, 2015; Putkinen et al., 2012). The LDN response has been recorded mainly in pre-school (Korpilahti, et al., 1995; Korpilahti, Krause, Holopainen & Lang, 2001; Maurer et al., 2003a; Čeponienė, Lepistö, Soininen, Aronen, Alku & Näätänen, 2003) and school-age children (Korpilahti et al., 1995; Čeponienė, Cheour & Näätänen, 1998; Cheour, Korpilahti, Martynova & Lang, 2001; Čeponienė, Yaguchi, Shestakova, Alku, Suominen & Näätänen, 2002; Shafer, Morr, Datta, Kurtzberg & Schwartz, 2005; Hommet et al., 2009; Datta et al., 2010; Bishop et al., 2011; Liu et al., 2014), along with newborns and even fetuses (Draganova, Eswaran, Murphy, Huotilainen, Lowery, & Preissl, 2005). Several studies suggest that LDN amplitude decreases with age between childhood and adulthood (Gumenyuk et al., 2004; 2001; Bishop et al., 2011; Määttä et al., 2005; Hommet et al., 2009; Müller, Brehmer, von Oertzen, & Lindenberger, 2008), thus indicating the maturation of cortical processing of yet unknown function. Nevertheless, some studies show evidence that this decrease is not linear (Liu et al., 2014) or that a small LDN magnitude cannot directly be taken as an index for more mature processing (Hong et al., 2018). Furthermore, even though LDN has been reported to be absent or nearly absent in adults (Müller et al., 2008; Liu et al., 2014), LDN-like responses have been found in adults (Alho et al., 1994; Horváth, Roeber, & Schröger, 2009; Peter, McArthur, & Thompson, 2012). However, it is not certain if these adult responses reflect the same functional process as LDN (see below).

The functional process underlying LDN response even in children is not well established. LDN has sometimes been referred to as the late MMN response, but in the light of previous studies this interpretation does not seem to be valid. In addition to its neural generators being distinct

from those of the MMN (Čeponienė et al., 2004; Hommet et al., 2009), the two components show distinct oscillatory activity (Bishop et al., 2010). Furthermore, the correlation of LDN amplitude size and the magnitude of deviance differ from those of MMN: whereas MMN amplitude has been shown to increase in accordance with increasing change in deviation (Sams, Paavilainen, Alho, & Näätänen, 1985; Pakarinen, Takegata, Rinne, Huotilainen & Näätänen, 2007), LDN amplitude seems to act differently and even display the opposite pattern, showing larger amplitudes for smaller deviants (Bishop et al., 2010). It has been suggested that LDN is more pronounced for phonemic or lexical sounds (Korpilahti et al., 2001; Korpilahti, Krause & Lang, 1996; Kuuluvainen et al., 2016), but several studies argue against this position, by demonstrating either prominent LDN responses for non-linguistic stimuli (Čeponienė et al., 1998; Čeponienė et al., 2004), no differences between these components elicited by speech and nonspeech stimuli (Čeponienė et al., 2002; Putkinen et al., 2012) or reporting results showing LDN responses to some but not other, almost similar linguistic stimuli (Männel, Schaadt, Illner, van der Meer & Friederici, 2017).

Another proposal is that the LDN is functionally linked to redirecting of attention, similar to adult Reorienting negativity, RON (Schröger & Wolff, 1998; Wetzel et al., 2006), as these responses have been recorded in children in similar paradigms as RON in adults (e.g., Gumenyuk et al., 2001; Horvarth et al., 2009). Indeed, some studies suggest that the LDN reflects attention reallocation to the ongoing task after task-irrelevant sound stimuli (Gumenyuk et al., 2001; Shestakova et al., 2003; Wetzel et al., 2006). This position is supported by a negative correlation between LDN magnitude and behavioral distraction in young children (Gumenyuk et al., 2001) and a positive correlation between the magnitudes of the LDN and the P3a (Shestakova et al., 2003). However, still another possible explanation is that the LDN reflects later, higher-order processing of the deviant stimulus following the initial change detection, indexed by MMN (Čeponienė et al., 1998; Čeponienė, Lepistö, Soininen, Aronen, Alku, & Näätänen, 2004).

Overall, the evidence for the functional significance of LDN is contradictory. In the light of the aforementioned evidence, it seems plausible or even probable that several distinct functions taking place in the same latency range contribute to the LDN. This would explain the differential patterns of LDN elicitation in childhood in varying experimental settings.

### **1.3. Links between neuropsychological measures and auditory ERPs**

According to some studies, neural and behavioral auditory discrimination of the same stimuli coincide in adults (Novitski et al., 2004; Winkler et al., 1999; Amenedo & Escera, 2000; Kujala et al., 2001a; Tiitinen et al., 1994; see, e.g., Kujala, Tervaniemi & Schröger, 2007) and children (Kraus, McGee, Carrell, Zecker, Nicol & Koch, 1996; Maurer et al., 2003a), for linguistic (Winkler et al., 1999; Kraus et al., 1996; Maurer et al., 2003a) and frequency (Novitski et al., 2004; Maurer et al., 2003a) deviants. Furthermore, association between more general linguistic skills and neural discrimination of speech-related sounds have also been reported. Within linguistic domain, children's test performance seems to have an association with their neurophysiological measures (Kujala et al., 2001b; Lovio et al., 2010; Lovio, Halttunen, Lyytinen, Näätänen & Kujala, 2012; Männel et al., 2017; Widmann et al., 2012; Maurer, Bucher, Brem & Brandeis, 2003b; Bishop et al., 2010; Hong et al., 2018), predominantly seen in the MMN or LDN responses (Kujala et al., 2001b; Lovio et al., 2010; 2012; Männel et al., 2017; Neuhoff, Bruder, Bartling, Warnke, Remschmidt, Müller-Myhsok & Schulte-Körne, 2012). However, most of the studies showing this association compare typically developing children to clinically diagnosed atypical ones (Lovio et al., 2010; Männel et al., 2017; Bishop et al., 2010; Hong et al., 2018; Maurer et al., 2003b; Neuhoff et al., 2012) or clinically diagnosed groups receiving and not receiving intervention (Kujala et al., 2001b; Lovio et al., 2012; Widmann et al., 2012). Thus, it seems that most of the found group differences in ERPs reveal only drastic contrasts in auditory discrimination and fail to show more subtle individual differences.

Nevertheless, there are studies revealing links between neurophysiological measures for phoneme contrasts and phonological and/or reading skills in typically developing children (Hämäläinen, Landi, Loberg, Lohvansuu, Pugh & Leppänen, 2018; Espy, Molfese, Molfese, & Modglin, 2004; Parviainen, Helenius, Poskiparta, Niemi & Salmelin, 2011; Kuuluvainen et al., 2016). However, the methods have varied substantially and thus, these studies fail to display a coherent idea of the correlation between auditory ERPs and linguistic proficiency. Still, some studies suggest that neurophysiological measures predict later outcomes in literacy tests (Kuhl et al., 2008) or differentiate typically developing children from children with dyslexia or SLI (Hämäläinen et al., 2013; Jansson-Verkasalo et al., 2004; Maurer et al., 2009).

However, the association between ERPs and behavioral measures is not always straightforward: dyslexic children do not always display different ERP patterns from typically developing children (Paul, Bott, Heim, Wienbruch, & Elbert, 2006). Overall, the evidence on the connections between psychophysiological and behavioral measures in linguistic tests is incoherent, which is at least for a large part due to methodological differences between studies. As the studies have used different cognitive and/or linguistic tests, different auditory stimuli, different presentation rates of the stimuli and so forth, the comparison of the results is somewhat demanding (see, e.g., Bishop, 2007).

Although most studies have focused on the associations between auditory ERPs and linguistic skills, there are also some studies finding links between ERPs and non-linguistic intelligence measures. Larger MMN amplitudes seem to be associated with better functioning in tests assessing intelligence in healthy adults (Houlihan & Stelmack, 2012; Light, Swerdlow & Braff, 2007) and in individuals with schizophrenia (Kawakubo et al., 2006; Light & Braff, 2005a, 2005b; Baldeweg, Klugman, Gruzelier & Hirsch, 2004) or autism (Weismüller et al., 2015). In children, MMN and/or LDN amplitudes have been found to correlate with intelligence measures in typically developing children (Partanen et al., 2013c; Liu, Shi, Zhang, Zhao & Yang, 2007) and in clinical groups (Mikkola et al., 2007; Bauer, Burger, Kummer, Lohscheller, Eyshodlt & Doellinger, 2009). However, the research covering this phenomenon is scarce, suggesting that it is either an understudied topic or that the published literature is biased. In addition, the definition of intelligence has varied in these studies and this makes the overall picture even more confusing.

## **1.4. Effects of music training in childhood**

Basic musical skills are typically adopted in childhood. Although at least some musical skills are partly heritable (see, e.g., Mosing, Madison, Pedersen, Kuja-Halkola & Ullén, 2014), it has been shown that music training affects brain structure (Hyde et al., 2009; Habibi et al., 2017) and neural auditory discrimination (Putkinen et al., 2014). Indeed, it has been suggested that musical expertise is a combination of aptitude, exposure and training (see Ullén, Hambrick & Mosing, 2015).

In addition to bringing about heightened abilities in auditory discrimination (Zuk et al., 2013; Du & Zatorre, 2017; Parbery-Clark, Skoe, Lam & Kraus, 2009), music training has been linked to advanced general cognitive abilities, such as intelligence (Schellenberg, 2004; Forgeard, Winner, Norton & Schlaug, 2008), executive functions (Bergman-Nutley, Darki & Klingberg, 2014; Jaschke, Honing & Scherder, 2018; Moreno, Bialystok, Barac, Schellenberg, Cepeda & Chau, 2011; Saarikivi, Putkinen, Tervaniemi & Huotilainen, 2016), social functioning (Kirschner & Tomasello, 2010; Schellenberg, Corrigall, Dys & Malti, 2015; Ritblatt, Longstreth, Hokoda, Cannon & Weston, 2013) and language (Degé & Schwarzer, 2011; Overy, 2003; Forgeard et al., 2008; François, Chobert, Besson & Schön, 2013).

#### **1.4.1. Effects of music training on linguistic skills**

A large body of evidence has shown that musical skills and training are associated with linguistic abilities. According to studies in adults, musicians outperform non-musicians in syllable discrimination (Zuk, et al., 2013) and detecting speech in noise (Du & Zatorre, 2017; Parbery-Clark et al., 2009) and foreign language pitch variations (Marques, Moreno, Castro & Besson, 2007), along with learning pseudo-words (Dittinger et al., 2016). Musical aptitude has an association with acquisition of foreign language sound structures both in adults (Slevc & Miyake, 2006; Milovanov, Pietilä, Tervaniemi & Esquef, 2010; Bhatara, Yeung & Nazzi, 2015) and children (Milovanov, Huotilainen, Välimäki, Esquef & Tervaniemi, 2008) along with children's reading skills and phonemic awareness (Anvari, Trainor, Woodside & Levy, 2002). Furthermore, musical experience correlates with verbal memory in adults (Chan, Ho & Cheung, 1998) and children (Ho, Cheung & Chan, 2003), children's detection of prosody (Magne, Schön & Besson, 2006), and their vocabulary (Forgeard, Winner, Norton & Schlaug, 2008) and reading skills (Corrigall & Trainor, 2011). Traditionally, musically trained participants in correlational studies have been adult instrumentalists (not singers) and children participating in individual instrumental training organized by music institutes (e.g., Chan et al., 1998; Ho et al., 2003; Milovanov et al., 2008; 2010; Magne et al., 2006; Forgeard et al., 2008).

Nevertheless, the correlation does not imply causality, and the aforementioned studies tell us only that musicians or musically trained children differ from their peers having no background in music training and fail to show how much this difference is due to musical training and how



much to other factors. However, a growing body of evidence suggests that there are also causal links between music and behaviorally measured language skills. Studies reporting such results have used as music interventions either individual instrumental training (Nan et al., 2018; Ho et al., 2003; Slater, Strait, Skoe, O'Connell, Thompson & Kraus, 2014; Roden, Kreutz & Bongard, 2012; Yang, Ma, Gong, Hu & Yao, 2014), computerized music skills training (Moreno et al., 2011; Bhide, Power & Goswami, 2013), or group music sessions including typically, e.g., joint singing, rhythmic exercises and training in auditory discrimination (Moritz, Yampolsky, Papadelis, Thomson & Wolf, 2013; Degé & Schwarzer, 2011; Overy, 2003; Flaunacco, Lopez, Terribili, Montico, Zola & Schön, 2015, François et al., 2013, Rautenberg, 2015; Moreno, Marques, Santos, Santos, Castro & Besson, 2009). Music interventions have been shown to enhance phonological awareness (Moritz, et al., 2013; Degé & Schwarzer, 2011; Overy, 2003; Flaunacco et al., 2015), word discrimination (Nan et al., 2018) and segmentation skills (François et al., 2013), verbal intelligence (Moreno, et al., 2011) and verbal memory (Roden et al., 2012; Ho et al., 2003), rapid naming skills (Slater et al., 2014), reading and literacy skills (Rautenberg, 2015; Slater, et al., 2014; Flaunacco, et al., 2015; Moreno, Marques, Santos, Santos, Castro & Besson, 2009; Bhide et al., 2013) and the academic scores for second language (Yang et al., 2014). These behavioral studies indicate that music interventions improve linguistic skills more than visual arts training (François, et al., 2013; Rautenberg, 2015; Flaunacco, et al., 2015; Moreno, et al., 2011; Moreno, et al, 2009) or sports (Degé & Schwarzer, 2011), and further show similar effects as grapheme-phoneme intervention (Bhide et al., 2013). The benefits of music are also clear when compared to groups receiving no active interventions (Yang et al., 2014; Roden et al., 2012; Ho et al., 2003; Slater, et al., 2014; Moritz et al., 2013; Nan et al., 2018). Children in the studies have been between the age 4 (Nan et al., 2018; Moreno et al., 2011) to approximately 9 years (Slater, et al., 2014) in the beginning of the intervention.

The aforementioned interventions have lasted from only 20 days (Moreno et al., 2011) to 18 months (Roden et al., 2012) and have varied in their intensity from two-hour daily training (Moreno et al., 2011) to one weekly session (Roden et al., 2012; Ho et al., 2003). In general, it looks that the more intensive the intervention is the faster the linguistic transfer effects are perceived. Even though there are studies not finding these transfer effects of music to language (Cogo-Moreira, Brandão de Ávila, Ploubidis & Mari, 2013; Swaminathan & Schellenberg,

2017), it seems plausible that at least to some degree, music activities do enhance linguistic skills and thus, speed up the development of these abilities in childhood.

#### **1.4.2. Effects of music training on neural speech-sound discrimination**

Musicianship shows benefits in tasks related to neural speech-sound detection. Musicians are faster learners in native vowel discrimination (Elmer, Greber, Pushparaj, Kühnis & Jäncke, 2017) and detect more accurately pitch contours in native (Schön, Magne & Besson, 2004) and foreign language (Marques et al., 2007). In addition, musicians are more advanced in detecting foreign-language phonemes (Intartaglia, White-Schwoch, Kraus & Schön, 2017; Marie, Delogu, Lampis, Belardinelli & Besson, 2011) and lexical tone changes (Marie et al., 2011a) and more sensitive to the metric structure of words (Marie, Magne & Besson, 2011). Furthermore, musically trained children are better in discriminating vowel duration and consonant changes (Chobert, Marie, Francois, Schön & Besson, 2011) and detecting pitch violations in sentences (Magne et al., 2006) at the neural level than their peers not trained in music. As music and language processing have been shown to activate the same brain regions (Maess, Koelsch, Gunter & Friederici, 2001; Levitin and Menon, 2003; Abrams, Bhatara, Ryali, Balaban, Levitin & Menon, 2010), it is not surprising that links between music training and linguistic processing have been found also on neural level.

Some longitudinal intervention studies have shown neural changes particularly in speech domain in children partaking in music activities. Music interventions have improved children's discrimination of lexical tone changes (Nan et al., 2018), phonemes (Kraus et al., 2014), vowel duration and consonant changes (Chobert et al., 2014) and segmenting speech sounds (Francois, Chobert, Besson & Schön, 2013). Furthermore, music interventions have affected children's neural processing for foreign-language phoneme discrimination (Carpentier, Moreno & McIntosh, 2016) and incongruous sentence endings (Moreno & Besson, 2006). The interventions in the aforementioned studies have lasted from four weeks (Carpentier et al., 2016) to two years (Francois et al., 2013; Kraus et al., 2014) and varied in the overall intensity.

There is less literature on the effects of music training on neural speech sound processing than there is on these effects on behaviorally measured linguistic skills, and more studies are needed.

### 1.4.3. Effects of music on intelligence and executive functions

According to some studies, musicians or musically trained children show superior skills compared to their non-musician peers in tests measuring intelligence or executive functions. Musical aptitude (Swaminathan, Schellenberg & Khalil, 2017), music training (dos Santos-Luiz, Mónico, Almeida & Coimbra, 2016; Schellenberg & Mankarious, 2012; Trimmer, C. & Cuddy, 2008; Schellenberg, 2011) and its duration (Degé, Kubicek & Schwarzer, 2011) seem to have a positive association with intelligence in children (Schellenberg & Mankarious, 2012; Forgeard et al., 2008; Bergman-Nutley et al., 2013), adolescents (dos Santos-Luiz et al., 2016; Bergman-Nutley et al., 2014) and adults (Silvia, Thomas, Nussbaum, Beaty & Hodges, 2016; Trimmer, C. & Cuddy, 2008). However, the children who partake in music lessons typically come from more privileged families (Corrigall, Schellenberg & Misura, 2013) and these studies do not necessarily demonstrate the benefits of solely music training.

Some evidence for causal links between music training and intelligence in children has also been found. In the pioneering study by Schellenberg (2004), one year in music intervention group enhanced randomly assigned children's scores in the intelligence tests more than participating in drama or passive control group. In line with this, music training has been found to enhance intelligence in other studies as well (Kaviani, Mirbaha, Pournaseh & Sagan, 2014; Bugos & Jacobs, 2012). However, in these studies the lack of active control groups limits the conclusions that can reliably be drawn from these reports: even if intelligence scores rise, it may be due to training per se and not specifically musical training. Overall, the number of studies revealing causal links between music and intelligence is scarce, and several studies have reported not finding these effects (Moreno, et al., 2011; Mehr, Schachner, Katz & Spelke, 2013; Nan et al., 2018).

*Executive functions* (EFs) is a broad concept referring to several capacities, typically attention, inhibition, set shifting, and working memory (Diamond, 2013). Some studies have found an association between music training and executive functions (Bergman-Nutley et al., 2014; Zuk, Benjamin, Kenyon & Gaab, 2014; Khalil, Mincses, McLoughlin & Chiba, 2013; see Dumont, Syurina, Feron & van Hooren, 2017), but only few of them have investigated causal effects of music on EF. In comparisons with active control groups, interventions with music training have improved executive functions, such as working memory (Roden, Grube, Bongard & Kreutz, 2014), inhibition (Moreno et al., 2011; Jaschke et al., 2018; Bugos & DeMarie, 2017) and

processing speed (Roden et al., 2012), and changes in event-related-potential components related to inhibitory control (Moreno et al., 2011).

However, there are also contradicting results from correlative (Schellenberg, 2011) and causal (Nan et al., 2018; Janus, Lee, Moreno & Bialystok, 2016) studies, and overall, the evidence promoting causality between music training and executive functions is fragmentary (see, e.g., Dumont et al., 2017; Jaschke, Eggermont, Honing & Scherder, 2013).

## 2. Aims of the thesis

The present thesis examines the maturation of pre-school children's neural speech-sound discrimination, the association between this discrimination and other linguistic skills, and the effects of music playschool on linguistic maturation. *Phoneme processing* and *Vocabulary* tests were chosen to measure the linguistic development in both Studies I and III, as the previous studies have shown that these abilities benefit at least from intensive music interventions. In addition, *Auditory closure* test was used in Study I for its clinical relevance.

*Study I* explored the relations between 5–6-year-old children's neural speech-sound discrimination and their linguistic skills and/or intelligence abilities. The ERP responses to changes in vowel identity, vowel duration, consonant, intensity and frequency were recorded in multifeature paradigm and compared to children's behavioral scores in *Phoneme processing*, *Auditory closure* and *Perceptual reasoning index* in order to reveal a possible association between cognitive abilities and speech-related neural indices. The non-verbal intelligence measures – as defined by tests from WISC IV test battery – were included because some previous evidence shows that they might be reflected in auditory discrimination.

In *Study II*, 5–6-year-old children's ERP responses were recorded four times within twenty months with the same multifeature paradigm used in Study I. The aim was to depict the maturation of distinct ERP components reflecting neural speech-sound discrimination.

*Study III* investigated the development of linguistic skills, along with perceptual reasoning and inhibitory skills in 5–6-year-old children partaking in kindergarten music playschool or dance lessons, or alternatively having no extra activity during the day care. The hypothesis was that children attending to music playschool would show enhanced development of linguistic skills compared to other children in the study. Whereas previous literature is incoherent about the effects of music training on intelligence, the effects of music training on executive functions has evoked a lot of interest lately. The tests for intelligence (perceptual reasoning) and executive functions (inhibitory skills) were included in the test battery to find out whether these abilities also benefited from music activities in the settings of the study.

### 3. Methods

#### 3.1. Participants

Originally 84 participants (54 girls) in two cohorts (1<sup>st</sup> cohort N=45, 2<sup>nd</sup> cohort N=39) were recruited from 14 municipal kindergartens in Helsinki metropolitan area. After the first year, the children started preschool, not all of which were at the same premises than the kindergartens. Altogether 26 kindergartens or/and preschools were involved in the research. Three participants dropped out from the study after the first measurement and two were excluded based on developmental delays. In addition, some children were further excluded from separate studies, based on missing or too noisy EEG data (Study I: 9 participants, Study II: 4 participants) or being non-native speakers of Finnish (Study III: 13 participants). The non-native Finnish speakers were excluded from Study III because they were over-represented in passive control group and could have distorted the results. However, the non-native participants were included in Studies I and II, and the language background (native or non-native) was included as a categorical between-subjects factor in Study I. Thereby, there were 70 participants in Study I, 75 participants in Study II and 66 participants in Study III.

**Table 1** The number of participants included in the studies along with the mean (standard deviation), minimum and maximum age at each test and EEG measurement time.

	Study	N	Age (months)		
			Mean (SD)	Minimum	Maximum
Neurocognitive assessments					
1 <sup>st</sup>	III	66	63 (4.4)	53	69
2 <sup>nd</sup>	I / III	70 / 66	69 (3.1) / 69 (3.6)	63 / 64	77 / 77
3 <sup>rd</sup>	III	64	75 (3.6)	68	83
4 <sup>th</sup>	III	64	81 (3.6)	75	89
EEG measurements					
1 <sup>st</sup>	II	74	63 (3.2)	57	69
2 <sup>nd</sup>	I / II	70 / 66	69 (3.1) / 70 (3.1)	63 / 64	77 / 77
3 <sup>rd</sup>	II	61	77 (3.1)	72	83
4 <sup>th</sup>	II	65	83 (3.2)	77	88

Children were followed for two school years. All the participants turned five during the calendar year of the beginning of the longitudinal study. The averaged ages for all participants on all test and EEG measurement points are listed in Table 1.

The guardians were informed about the research in writing and they signed a written informed consent. The children gave their verbal assent before the experiment. The experiment protocol was approved by The Ethical Committee of the Humanities and Social and Behavioral sciences in the University of Helsinki, Finland, and the experiments were carried out in accordance with the committee's guidelines and regulations as well as with those of Helsinki declaration.

The guardians filled a questionnaire about children's family background and extra-curricular activities in the beginning of the study and were asked to inform about the possible change in these activities in the end of the follow-up.

### **3.2. Music and dance interventions**

Music playschool is a traditional, common Finnish extra-curricular activity where a considerable number of parents take their offspring during the early childhood. It is typically organized by non-profit organizations which provide lessons for low cost (appr. 100€/semester) or even for free for very low-income families. The teachers are professional music educators with a degree in Bachelor's or Master's programme and are specialized in teaching small children. Music playschool lessons consist of rhyming, singing, listening and moving to music, playing simple instruments (small drums, triangles, xylophones etc.) and playing games along with body percussions aimed at improving fine and gross motor skills. Even though the individual lessons differ from each other they all include similar elements such as singing and synchronizing motor actions with other children and with the beat. The lessons welcome children who are 3-4 months old (or any time after that) with their parents or other guardians. When children get 2-3 years old, they join the lessons on their own until the school age (7 yrs).

Dance lessons for pre-schoolers in Finland are increasingly popular, but do not have such a long history as music playschools. They are typically costlier since they are seldom organized by non-profit organizations and thus less available to all children. The dance teachers typically have a bachelor's degree in dance and pedagogy, but most of the teachers have not focused on teaching small children in their studies. The aims of children's dance lessons in Study III – and in general – are in developing children's percept of rhythm, space and their own body along with acting in a group. Exercises include practicing elementary motor skills, moving to rhythms, basic improvisation skills and moving in group. Like with music playschools, individual lessons

differ somewhat, but are typically built on similar elements. With both music playschool and children's dance lessons, the focus is on playfulness and familiarizing children with music making and dance, and – maybe – inspiring them to continue more intensive participation in school-age. Practice at home is typically neither suggested nor prohibited.

In some Finnish cities, music institutes offer music playschool lessons and dance institutes dance lessons implemented in kindergartens with a moderate cost of approx. 100 €/ semester and free for very low-income families. This makes participating in either one of these activities more likely to wider range of families, especially for those who have no resources in taking their children to lessons outside kindergartens after a workday, possibly to another part of the town.

In the particular city in Helsinki metropolitan area where the research was conducted, the music and dance institutes offered lessons in municipal kindergartens. Kindergartens decided for themselves if they wanted to provide either activity to the children; agreeing to both of them was not possible. Out of the 26 kindergartens and preschools recruited in the research, nine offered children a possibility to attend to professionally taught music playschool and eight professionally taught dance lessons. Nine kindergartens did not provide any extra-curricular activities by outside institutes. Music playschool and dance lessons took place during the day-care once a week at the kindergarten premises, 30 times a year. Both activities were held in groups of 8–12 children and lasted 45 minutes.

There were no differences between the number of teachers and the level of their education between the kindergartens. The dance kindergartens in Study III were located socio-economically in slightly more advanced areas but such a difference did not exist between music and passive control kindergartens. Municipal kindergartens in Finland are of high quality and they cost 0–300 € per month depending on the income of the family. Musical activities are a part of Finnish kindergartens' curricula, and kindergarten teacher's studies (Bachelor's/Master's degree) include teaching of music activities. Early childhood education plan that is followed in all Finnish municipal kindergartens (such as the ones in Study III) includes also weekly music. The realization of these music sessions, naturally, varies between kindergartens according to the skills and interests of the personnel as well as space, instruments, and audio technology available.



During each follow-up year, the personnel teaching the children participating in the studies filled a questionnaire about self-provided musical activities in kindergarten. The monthly amount of these music activities varied substantially between children [average over two years; mean=163 minutes; SD=82; max=390; min=60]. For a closer look, the kindergartens were divided in four groups according to the amount of self-provided musical activities, not including the music playschool and dance lessons in focus of Study III. According to a  $\chi^2$ -test, there was no difference in the average amount of self-provided music activities between the three types of kindergartens, namely those that offered additional music playschool, those offering additional dance lessons or those having no additional activity organized by an outside institute [ $\chi^2(6)=6.841$ ,  $p=.336$ ]. In other words, the kindergartens providing these extra music playschool lessons by professional music playschool teachers did not offer any more self-provided music activities by kindergarten teachers than the other type of kindergartens.

The interventions were provided by music and dance institutes, and children's participation in them could not be restricted or guided for the purposes of the research. In addition to music or dance in kindergarten, some children partook the other studied extra-curricular activity outside the kindergarten. Furthermore, some children had started music playschool or dance lessons already before the start of the study. To take all these variations into account in the analyses, music playschool and dance lessons both in and outside kindergartens were included in each child's total number of months of participation. Thus, instead of group comparisons, the number of months each child had spent in music playschool or/and dance lessons by the end of the follow-up acted as continuous predictors for the test scores in Study III. Twenty-eight children (female N=19) had participated in music playschool after turning three, the number of months varying between 9 and 36. Similarly, thirty-two (female N=26) had participated in dance lessons, the number of months varying between 1 and 40. Twenty kindergarteners (female N=8) had not participated in either music playschool or dance lessons by the end of the follow-up.

### **3.3. Neurocognitive assessments (Studies I and III)**

The children were tested with six subtests from three test batteries, namely NEPSY II (A Developmental Neuropsychological Assessment: Korkman, Kirk & Kemp, 2008), WISC IV (Wechsler intelligence scale for children: Wechsler, 2010) and ITPA (Illinois Test of

Psycholinguistic Abilities: Kirk, McCarthy & Kirk, 1972). Both NEPSY II and WISC IV are internationally used test batteries for assessing neuropsychological development of children. The internal reliability and validity of NEPSY II are very good (Brooks, Sherman & Strauss, 2009; Korkman, Kirk & Kemp, 2007), and although the validity of WISC has been discussed (Kaufman, Flanagan, Alfonso & Mascolo, 2006), it is the most widely used intelligence battery for children (Wechsler, 2010; Kaufman et al., 2006). ITPA is regularly used by Finnish and Scandinavian speech therapists because of its ability to differentiate children with specific language impairment (SLI) from typically developing children (Hannus, Kauppila, Pitkaniemi & Launonen, 2013).

The children were tested with *Phoneme processing* and *Inhibition* (NEPSY II), *Vocabulary*, *Matrix reasoning* and *Block design* (WISC IV), and *Auditory closure* (from ITPA) tests. For the analyses, *Matrix reasoning* and *Block design* were combined according to WISC IV guidelines to form *Perceptual reasoning index*, an index for non-verbal intelligence. The scores for *Phoneme processing*, *Auditory closure* and *Perceptual reasoning index* were analysed in Study I and the scores for *Phoneme processing*, *Vocabulary*, *Inhibition* and *Perceptual reasoning index* in Study III.

The *Phoneme processing* (PP) subtest measures phonological awareness and auditory memory. In the first section the child is shown pictures of objects and hears names for them. The experimenter then pronounces a phoneme combination that is included in one of the object names. The child is asked to point out the correct object. In the next section the experimenter utters a word and asks the child to remove a phoneme or combination of phonemes from it and say the resulting word. The original word might be for example /tak:a/ (fireplace) from which the experimenter asks to remove /t/. The right answer would then be /ak:a/, (an old woman). In the final section, the child is asked to replace a phoneme with another. For instance, the experimenter asks him/her to replace /i/ in the word /helmi/ (pearl) with /a/. Thus, the resulting word would be /helma/ (hem of skirt). After six consecutive wrong answers the testing is stopped.

*Vocabulary* (VOC) subtest measures verbal knowledge and the ability to form concepts. The child is asked to define the meaning of orally presented words which become increasingly difficult. The sophistication of definition is scored with 0, 1 or 2 points. E.g., “cow” could be answered “animal”, “mammal”, “domestic animal” (2 points), “you can milk cows”, “says moo”

(1 point), or “eats grass”, “calf” (0 points). After five consecutive answers given zero points the testing is stopped.

*Auditory closure* (AC) subtest investigates the ability to produce a complete word out of an incomplete one. This test’s theoretical background is not as solid as with NEPSY II and WISC IV, but it was included in the linguistic test battery because of its clinical relevance and because of an interest to see if it has a correspondence with neurophysiological measures. In the test, the experimenter pronounces an incomplete word that is missing a phoneme or phonemes from the beginning, from the middle or from the end. The child is asked to supplement the word to make it a proper one. In most of the tasks more than one option is accepted. E.g., /avai/ could be either /avain/ (key) or /avaimet/ (keys). After six consecutive wrong answers the testing is stopped.

*Inhibition* (INH) subtest measures inhibition and task shifting, two central components of executive functions. In Study III, only the first two sections of the test were conducted, excluding the section measuring task shifting abilities. According to some studies, inhibitory control correlates almost perfectly with common executive functions (Friedman, Miyake, Young, DeFries & Corley, 2008; Friedman, Miyake, Robinson & Hewitt, 2011). In the test, the experimenter first asks the child to tell the orientations of shown arrows depicted on a sheet of paper. In the second section testing inhibition the child is asked to tell the opposite of the orientation of each arrow. Then the test is repeated with circles and squares replacing arrows. The child is first asked to tell the shapes of the objects and in the second section say “circle” at the place of squares and vice versa. Answers are timed and both the number of correct answers and the time to finish the test are contributing to the scores.

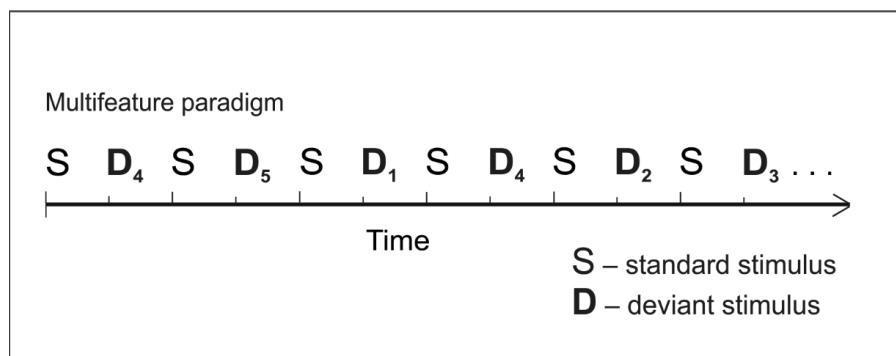
*Block design* is a measure for visuospatial skills. The experimenter shows the child a red-and-white pattern in a picture. The child is asked to form the same pattern with red-and-white blocks as fast as possible and the performance is timed. *Matrix reasoning* measures fluid reasoning skills. In the test the child sees an array of three pictures. He/she is then asked to select from five options the picture that fits logically the array. In Studies I and III, the tests were combined according to instructions in WISC-IV, to form *Perceptual Reasoning Index* (PRI) that acts as an indication of non-verbal intelligence.

In the analyses, the raw scores for *PP*, *VOC* and *AC* and standard scores for *PRI* and *INH* were used.

### 3.4. ERP experiments (Studies I and II)

#### 3.4.1. Stimuli

The stimuli were presented in a multifeature paradigm (Näätänen et al., 2004), where every other stimulus in a sound stream is a standard and every other a deviation (Figure 1). While in a traditional oddball paradigm the standard stimuli occur 70–90% of all the stimuli, in a multifeature paradigm they occur only 50% of the time. However, the other 50% of the stimuli are not comprised of only one or two but typically at least four deviating stimulus types and thus, each deviant type appears typically only in 10% of the stimuli. It is essential that each of these stimulus types differ from the standard in only one feature, e.g., frequency, location, vowel content, initial consonant, duration, etc. This way, one deviant stimulus acts as a standard for the other deviant types.



**Figure 1** Schematic illustration of the multifeature paradigm. D<sub>1</sub>-D<sub>5</sub> stand for different deviant types used in the paradigm.

According to studies (Näätänen et al., 2004; Pakarinen et al., 2009; Kujala et al., 2006), adults' ERP responses for the same stimuli in oddball and multifeature paradigms are reasonably similar. Furthermore, the same correspondence has been found in children (Lovio et al., 2009; Partanen et al., 2013b; Partanen et al., 2013c). With children, the multifeature paradigm is an ideal tool: it allows us to collect a large amount of data in short time.

The stimulus sounds in the used paradigm were made with semisynthetic Speech Generation Method (for details, see Alku, Tiitinen & Näätänen, 1999). The experiment included four blocks:

phoneme combination /pi:/ acted as standard ( $P = .50$ ) in two of them and /te:/ ( $P = .50$ ) in other two. The deviant stimulus types were consonant change CON ( $P = .10$ ), vowel change VOW ( $P = .10$ ), vowel duration change DUR ( $P = .10$ ), intensity change INT (louder  $P = .05$  and softer  $P = .05$ ) and frequency change FRE (higher  $P = .05$ , lower  $P = .05$ ). All the stimuli are presented in more detail in Table 2. Stimulus onset asynchrony was 500 ms and sound duration was 170 ms, except for vowel duration deviant DUR that had the duration of 100 ms. F0 was 101 Hz for all the stimuli, excluding deviants FRE that had either 93 Hz (low) or 109 Hz (high) as F0s. Intensity of the stimuli was  $\sim 70$  dB (SPL) excluding the intensity deviants that were 63 dB (softer) and 77 dB (louder). There were 465 stimuli in each of the four blocks, order of which was counterbalanced.

**Table 2** The stimuli of the multifeature paradigm. Four blocks (two blocks for each standard stimuli) were played for the participants. The blocks were played in randomized order.

Block	STD	VOW	DUR	CON	INT	FRE
1 & 2	/te:/	/ti:/	/te/	/pe:/	$\pm 7$ dB	$\pm 8$ %
3 & 4	/pi:/	/pe:/	/pi/	/ti:/	$\pm 7$ dB	$\pm 8$ %

### 3.4.2. Data recording and processing

The experimental paradigm was implemented with Presentation 17.0 (Neurobehavioral Systems, Inc., CA, US). The EEG was recorded with 32 Ag-AgCl scalp electrodes according to international 10-20 system by using ActiCap (Brain Products, Germany) and the portable equipment included Brainvision QuickAmp amplifier. The EEG data were registered with sampling rate of 500 Hz. Recording reference was the average signal of all electrodes. Two additional active electrodes were placed on the mastoid bones behind ears.

EEG was processed with BESA 5.3. software (MEGIS Software GmbH, Gräfelting, Germany). We interpolated noisy electrodes and removed eye blink artefacts using semi-automatic BESA PCA method. The percentage of accepted trials averaged over all participants and the number of interpolated channels averaged over all blocks for each measurement are listed in Table 3. Frequencies under 0.5 Hz and over 30 Hz were filtered out offline and the data were re-referenced to the mean of the mastoids. Inspected epochs were extracted from EEG from -100 ms before onset to 500 ms after the onset of the stimuli. EEG epochs with amplitudes exceeding  $\pm 120$   $\mu$ V were excluded from the analyses. The responses were averaged for each participant

and the averaged responses were then exported to (Study I) MATLAB R2012 or (Study II) MATLAB R2017 (The MathWorks Inc., MA, US).

**Table 3** The percentage of accepted trials and the number of interpolated channels. The accepted trials are averaged over all participants and interpolated channels over all blocks (4 blocks per a participant) for each measurement. The interpolated channels are reported for both all 32 channels used in the measurements and for 9 channels (F3, Fz, F4, C3, Cz, C4, P3, Pz and P4) used in the analyses.

	Measurements				
	Study II				Study I
	1 <sup>st</sup> (N=74)	2 <sup>nd</sup> (N=66)	3 <sup>rd</sup> (N=61)	4 <sup>th</sup> (N=65)	2 <sup>nd</sup> (N=70)
<b>Accepted trials (percentage)</b>					
mean (SD)	93.3 (5.9)	93.6 (5.3)	92.7 (6.1)	95.0 (4.6)	93.4 (5.3)
max	99.3	99.2	99.2	99.3	99.2
min	67.0	67.1	69.0	66.5	67.1
median	94.8	95.5	93.8	96.1	95.4
<b>Interpolated channels (number)</b>					
Out of 32 channels					
mean (SD)	2.0 (1.5)	2.4 (1.8)	2.2 (1.4)	2.1 (1.4)	2.6 (2.0)
max	7	8	8	7	10
min	0	0	0	0	0
median	1	2	2	2	2
Out of 9 channels					
mean (SD)	0.69 (0.71)	0.72 (0.71)	0.59 (0.65)	0.43 (0.58)	0.74 (0.74)
max	3	3	3	3	4
min	0	0	0	0	0
median	1	1	1	0	1

The standard and deviant trials from all four blocks were combined according to their stimulus category. Responses to intensity deviant were further averaged over both intensity changes (louder and softer) and similarly, responses for the frequency deviant were averaged over increments and decrements of frequency. The averaged standard responses were subtracted from the average deviant responses for each deviant stimulus to create subtraction waveforms, separately for each participant. In both studies including EEG data (Studies I & II), the electrodes F3, Fz, F4, C3, Cz, C4, P3, Pz and P4 were further inspected. This is typical for ERP research, as it reveals some information about front-back and left-right distribution of the brain responses.

In Study I, mean amplitudes for MMN were calculated over the same 50 ms time window (200–250 ms) for all deviants except vowel duration, for which the time window 225–275 ms was used. For LDN, the same time window (375–425 ms) was used for all deviants. In Study II, the mean amplitudes were calculated separately for each deviant and each measurement for the MMN, LDN and P3a responses over 50 ms time window.

### 3.5. Procedure

All the tests and measurements were conducted in the kindergartens during the regular day care. The participant and the experimenter(s) were in separate room that was as quiet as possible. The neurocognitive tests and EEG measurements were not conducted on the same day. One experimental session included one (neurocognitive tests) or three (EEG measurements) breaks during which the child was offered cookies and juice. After the session children were given a sticker. The neurocognitive testing took 45–60 minutes and EEG measurement (including preparation and cleaning) 60 minutes per child. Children watched an animated movie during the EEG preparation and continued watching it – muted – during the experiment. They were asked to avoid unnecessary movement, to ignore the experimental stimuli, and to concentrate on the movie. The stimuli were presented via Sony Professional MDR-7506 headphones.

### 3.6. Statistical analyses

As Study I was cross-sectional it was feasible to use Analysis of Variance. Test scores for *Phoneme processing*, *Auditory closure* and *Perceptual reasoning index* acted as within-subjects covariates and native language as between-subjects factor in three-way repeated measures ANOVA (5 deviant types x 3 front-back electrode lines x 3 left-right electrode lines). If sphericity could not be assumed, Greenhouse-Geisser correction was applied. Second EEG measurements and tests were chosen for the analysis in Study I. The first measurements were not used due to the first cohort's first measurements and tests not being conducted within a reasonable temporal proximity of each other.

Typical problems in longitudinal ERP-studies are subjects either dropping out before the end of the follow-up or showing too much noisy data, both resulting in missing values. To avoid losing a considerable number of participants in such studies, it is recommendable to conduct analyses with Linear mixed model that allow including participants with some missing values. In longitudinal studies (II and III), a *linear growth curve model* (West, 2009) was used. In addition to being able to include participants with missing values, the model takes into account individual time-dependent variables for each measurement, i.e., age in Study II and testing day

in Study III. With this method one is able to build a model that places each value of a given variable (e.g., test score or MMN amplitude) in its individual place along the timeline. In Study II, the method enabled including children's individual ages at each measurement point in the model and in Study III it helped to overcome the problem with considerable variation existing between the first test times of the two cohorts. The downside of the Linear mixed models is that there is no generally accepted way to measure effect sizes. Instead of these, the parameter estimates (estimates of fixed effects) are reported in the results chapter. However, the parameter estimates are not absolute values but depend on the scale of the variables (e.g. months in the case of music playschool and days in the case of measurement day), and the effort is made to give the idea of this magnitude to the reader.

**Table 4** The analysis methods, predictors and dependent variables for all three studies. In Study II, the analyses were conducted separately for each response component, the mean amplitude averaged over F3, Fz, and F4 electrodes acting as the dependant variable for the MMN and P3a responses and the mean amplitude averaged over F3, Fz, F4, C3, Cz, C4, P3, Pz, and P4 electrodes acting as the dependant variable for the LDN response. In Study III, the analyses were conducted separately for each test.

Study	I	II	III
<i>Methods</i>	EEG Neurocognitive tests	EEG	Neurocognitive tests
<i>Data point(s)</i>	2 <sup>nd</sup> measurement	Measurements 1–4	Measurements 1–4
<i>Analysis</i>	repeated measures ANOVA	linear growth curve model	linear growth curve model
<i>Predictors</i>	Continuous: Test scores for <i>Phoneme processing</i> <i>Auditory closure</i> <i>Perceptual reasoning</i> <i>index</i>  Categorized: native language	Continuous: age mother's education	Continuous: measurement day mother's education music playschool dance lessons
<i>Dependent variables</i>	MMN and LDN response amplitudes	MMN, P3a and LDN response amplitudes	Test scores for <i>Phoneme processing</i> <i>Vocabulary</i> <i>Perceptual reasoning</i> <i>index</i> <i>Inhibition</i>

In Studies I, II and III, there were no group comparisons. Individual test scores acted as predictors in Study I. In Study II the predictors were children's individual age (in months) and



mother's education and in Study III the individual number of months in music playschool and dance lessons, measurement time (in days) and mother's education acted as predictors. As no groups were compared in these studies, there is no standardized formula to provide post hoc tests. Instead of these, figures with arbitrary cut-off points are presented in Studies II and III to illustrate the tendency of the significant differences. The analysis methods for all the studies are listed in Table 4.

In Study II a *Linear growth model* was created separately for each inspected response component, namely the MMN, P3a and LDN. Centred values for age (months) and mother's education (scale from 1–7), along with interaction between these, acted as predictors. For MMN and P3a, amplitudes averaged over front-line electrodes  $[(F3 + Fz + F4)/3]$  and for LDN amplitudes averaged over nine electrodes  $[(F3 + Fz + F4 + C3 + Cz + C4 + P3 + Pz + P4)/9]$  were set as dependent variables.

In Study III, a *Linear growth model* was created separately for each neurocognitive test, test scores acting as dependent variable. Centred values for time, duration of music playschool and dance lessons (months by the end of the follow-up) and mother's education, along with all the interactions between these acted as predictors. Time was indexed by children's individual test days. The first test day was marked as 1 and, e.g., a test day a week later was marked as 8. This resulted in a time-line where the first tests were conducted between days 1–150, second between days 201–255, third 412–455 and the fourth between days 573–624.

Random intercept model was used in all analyses and compound symmetry was chosen as the covariance structure on the basis of Schwarz's Bayesian Criterion (BIC) in both studies conducted with linear growth curve model. All the analyses were conducted with SPSS 24 (IBM Corporation, NY, USA), and the alpha level was set at  $p < 0.05$ . Only the significant main effects and interactions are reported in the results.

## 4. Results

### 4.1. Associations between neurocognitive assessments and auditory ERPs (Study I)

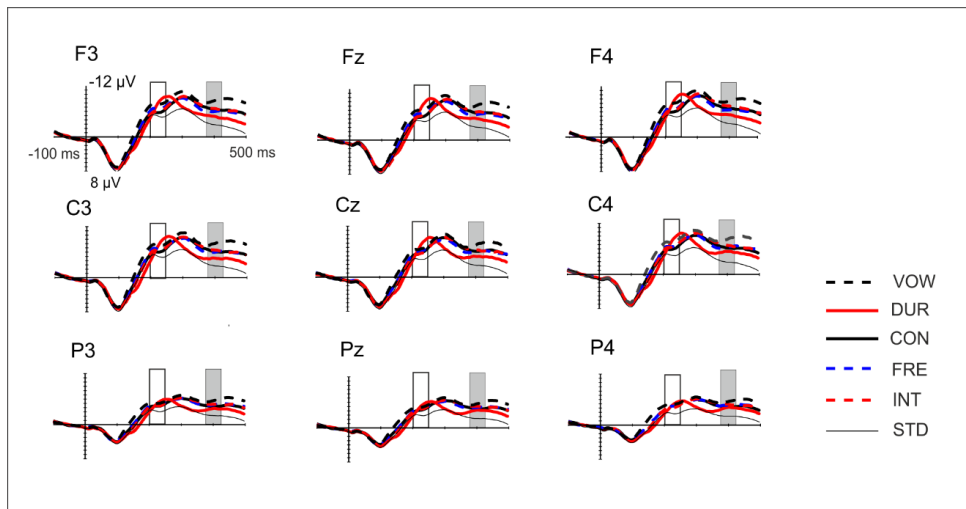
The average test results for the behavioral test scores (PP, AC, PRI) for Study I are shown in Table 5 and the mean MMN and LDN amplitudes for all children at Fz are listed in Table 6. All the MMN and LDN responses were significant in the inspected time windows ( $p < .001$ , each). The deviant and standard responses for the combined conditions in second measurement for all participants are depicted in Figure 2. Only the significant results are reported.

**Table 5** The mean (SD), minimum and maximum scores for the tests used in Study I.

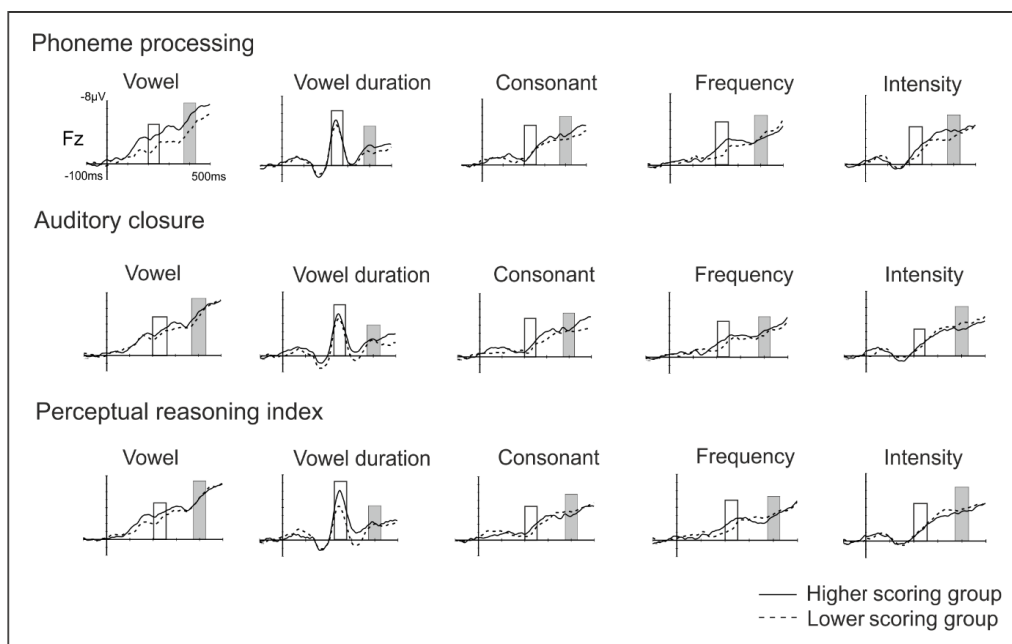
Test	Mean (SD)	All N=70 (female N=44)	
		Minimum	Maximum
<i>Phoneme processing</i>	27.6 (3.6)	18	41
<i>Auditory closure</i>	14.0 (3.3)	5	20
<i>Perceptual reasoning index</i>	29.4 (8.1)	12	48

**Table 6** The mean amplitudes for all measurements for all participants. Study I: The mean (SD) MMN (225–275 ms for vowel duration deviant, 200–250 ms for all the other deviants) and LDN (375–425 ms) amplitudes at Fz. Study II: The mean (SD) MMN, P3a and LDN amplitudes. The mean amplitudes for the MMN and the P3a are averaged over F3, Fz and F4 electrodes and for the LDN, over F3, Fz, F4, C3, Cz, C4, P3, Pz and P4 electrodes.

Measurement	Amplitude (SD)				
	1 <sup>st</sup> (Study II)	2 <sup>nd</sup> (Study II)	2 <sup>nd</sup> (Study I)	3 <sup>rd</sup> (Study II)	4 <sup>th</sup> (Study II)
<i>MMN</i>					
VOW	-2.0 (2.6)	-2.6 (2.6)	-2.7 (3.0)	-3.4 (3.0)	-2.9 (2.8)
DUR	-3.7 (2.4)	-4.1 (2.9)	-4.2 (3.0)	-4.8 (3.1)	-4.6 (2.4)
CON	-2.3 (2.2)	-2.8 (2.5)	-1.1 (2.4)	-2.8 (2.5)	-2.6 (2.1)
INT	-2.7 (2.4)	-2.9 (2.2)	-1.2 (2.2)	-2.3 (2.5)	-2.4 (2.0)
FRE	-2.0 (2.5)	-2.6 (2.6)	-1.8 (2.9)	-3.1 (2.9)	-2.6 (2.8)
<i>P3a</i>					
VOW	-4.4 (2.6)	-4.0 (2.8)	-	-3.4 (2.9)	-1.4 (2.9)
DUR	-0.2 (3.0)	-0.3 (2.3)	-	-0.1 (2.5)	-0.2 (1.9)
CON	-3.1 (2.3)	-3.3 (2.6)	-	-3.8 (2.4)	-3.2 (2.3)
INT	-3.0 (2.5)	-3.6 (2.4)	-	-3.3 (2.3)	-2.3 (2.0)
FRE	-2.5 (2.2)	-2.5 (2.4)	-	-2.0 (2.6)	-0.7 (2.7)
<i>LDN</i>					
VOW	-5.6 (2.7)	-5.8 (3.2)	-5.1 (3.1)	-6.1 (2.8)	-5.3 (2.5)
DUR	-1.7 (2.4)	-1.8 (2.2)	-1.8 (2.7)	-2.0 (2.1)	-1.7 (1.9)
CON	-3.5 (2.2)	-3.6 (2.4)	-3.4 (2.6)	-4.00 (2.4)	-3.0 (2.2)
INT	-3.7 (2.1)	-3.9 (2.4)	-3.7 (2.8)	-3.7 (2.2)	-2.9 (2.2)
FRE	-3.9 (2.3)	-3.6 (2.3)	-3.0 (2.5)	-4.4 (2.1)	-3.4 (2.3)



**Figure 2** Standard and deviant responses for combined conditions for all participants. White blocks show the inspected MMN time windows (200–250 ms) for all but vowel duration deviants (DUR time window 225–275 ms) and grey blocks the inspected LDN time windows (375–425 ms for all deviants).



**Figure 3** Averaged subtraction waveforms at Fz electrode for higher and lower scoring groups in each test, for all deviants. The groups were divided based on median scores of the tests (arbitrary cut off-point chosen for illustration purposes). Top: both *Phoneme processing* groups' responses at Fz electrode for all deviants ( $N_{\text{high}}=31$ ,  $N_{\text{low}}=39$ ). Middle: both *Auditory closure* groups' responses at Fz electrode for all deviants ( $N_{\text{high}}=28$ ,  $N_{\text{low}}=42$ ). Bottom: both *Perceptual reasoning index* groups' responses at Fz electrode for all deviants ( $N_{\text{high}}=33$ ,  $N_{\text{low}}=37$ ). White blocks mark the inspected MMN and grey blocks the inspected LDN time windows.

According to analysis conducted with rANOVA, test scores for *Phoneme processing* in second measurement had a significant main effect on the MMN in the second measurement [ $F(1)=4.315, p=.042$ ]. The main effects of the test scores in *Auditory closure* or *Perceptual reasoning index* on the MMN responses were not significant [ $F(1)=.508, p=.479$  and  $F(1)=1.700, p=.197$ , respectively], and neither was subjects' native language [ $F(1)=.056, p=.308$ ]. These results indicate that children with higher scores on the *Phoneme processing* test show larger MMN amplitudes relative to children with lower scores (Figure 3).

The only significant interaction contributing to MMN responses was Left-Right x PRI [ $F(2, 130)=3.271, p=.041$ ]. As post hoc comparisons the estimated mean amplitudes over the left, centre and right electrode lines with PRI scores set at the first or the third quartile, were compared. The comparisons indicated that the MMN responses of children with higher scores were equally distributed over left-right division [with higher quartile scores (35): Left: Mean =  $-2.1 \mu V$ ; Central: Mean =  $-2.0 \mu V$ ; Right: Mean =  $-2.1 \mu V$ ; significance of differences between Left-Right lines: Left vs. Central  $p=.596$ , Left vs. Right  $p=.962$ , Central vs. Right  $p=.581$ ]. Instead, children with lower scores showed significant right-side dominance of the responses [with lower quartile scores (24): Left: Mean =  $-1.6 \mu V$ ; Central: Mean =  $-1.6 \mu V$ ; Right: Mean =  $-1.9 \mu V$ ; significance of differences between Left-Right lines: Left vs. Central  $p=.726$ , Left vs. Right  $p=.042$ , Central vs. Right  $p=.026$ ].

For the MMN responses, no other significant main effects or interactions were found. Furthermore, no significant main effects or interactions were found on the LDN time window.

## **4.2. The maturation of auditory ERPs and the development of test performance (Studies II and III)**

All the analyses were conducted with *linear growth curve model*. Regarding the ERPs, parameter estimates indicate how many microvolts the inspected response amplitudes change when independent variables with significant main effects or interactions rise one step (months for age, steps on a scale from 1 to 7 for mother's education). Similarly, in connection with test scores, parameter estimates indicate how many points the inspected test scores change when independent variables with significant main effects or interactions rise one step (days for measurement days, months for music playschool and dance lessons, steps on a scale from 1 to

7 for mother's education). Of importance here is that since different tests have different scales for scores, the parameter estimates between scores for separate tests are not comparable. All the test scores are outlined in Table 7 and the peak latencies defining the chosen time windows in Study II are outlined in Table 8. The mean amplitudes for each response, each deviant and each measurement are listed in Table 6. All the MMN and LDN responses were significant in the inspected time windows ( $p < .001$ , each). The P3a response for all deviants differed significantly from zero ( $p < .001$ , each), excluding the vowel duration deviant in all of the four measurements ( $p = .665$ ,  $p = .256$ ,  $p = .764$  and  $p = .342$ , respectively) and the frequency deviant in the fourth measurement ( $p = .055$ ) (Study II). Only the significant or marginally significant results from Studies II and III are reported.

No significant main effects of or interactions with music and dance on the ERP responses were found in the preliminary analyses of Study II. Thus, in the published article, only age and mother's education act as factors. Yet, as the impact of music playschool was in the original focus of Study II, this result will be discussed in section 5.3.2.

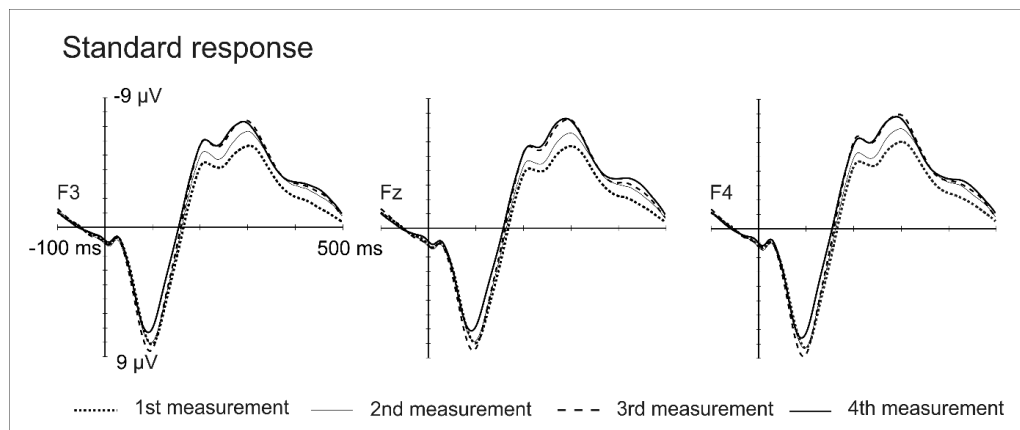
**Table 7** The mean (SD), minimum and maximum scores for the tests.

All (N=66, female N=41)			
	Mean (SD)	Minimum	Maximum
<i>Mother's education</i>	4.8 (1.4)	1	7
<i>Phoneme processing</i>			
Test 1	26.3 (2.7)	20	33
Test 2	28.1 (3.6)	22	41
Test 3	29.2 (4.4)	21	44
Test 4	33.0 (5.3)	23	47
<i>Vocabulary</i>			
Test 1	12.1 (4.3)	4	26
Test 2	13.4 (4.9)	5	25
Test 3	15.2 (5.5)	6	29
Test 4	17.8 (4.9)	8	28
<i>Perceptual reasoning index</i>			
Test 1	27.4 (8.4)	15.0	49.5
Test 2	30.0 (8.2)	12.0	48.0
Test 3	32.4 (7.6)	16.5	49.5
Test 4	34.6 (7.2)	18.0	49.5
<i>Inhibition</i>			
Test 1	8.9 (2.7)	4	15
Test 2	9.1 (2.9)	5	15
Test 3	9.8 (3.0)	4	16
Test 4	10.0 (2.8)	5	15

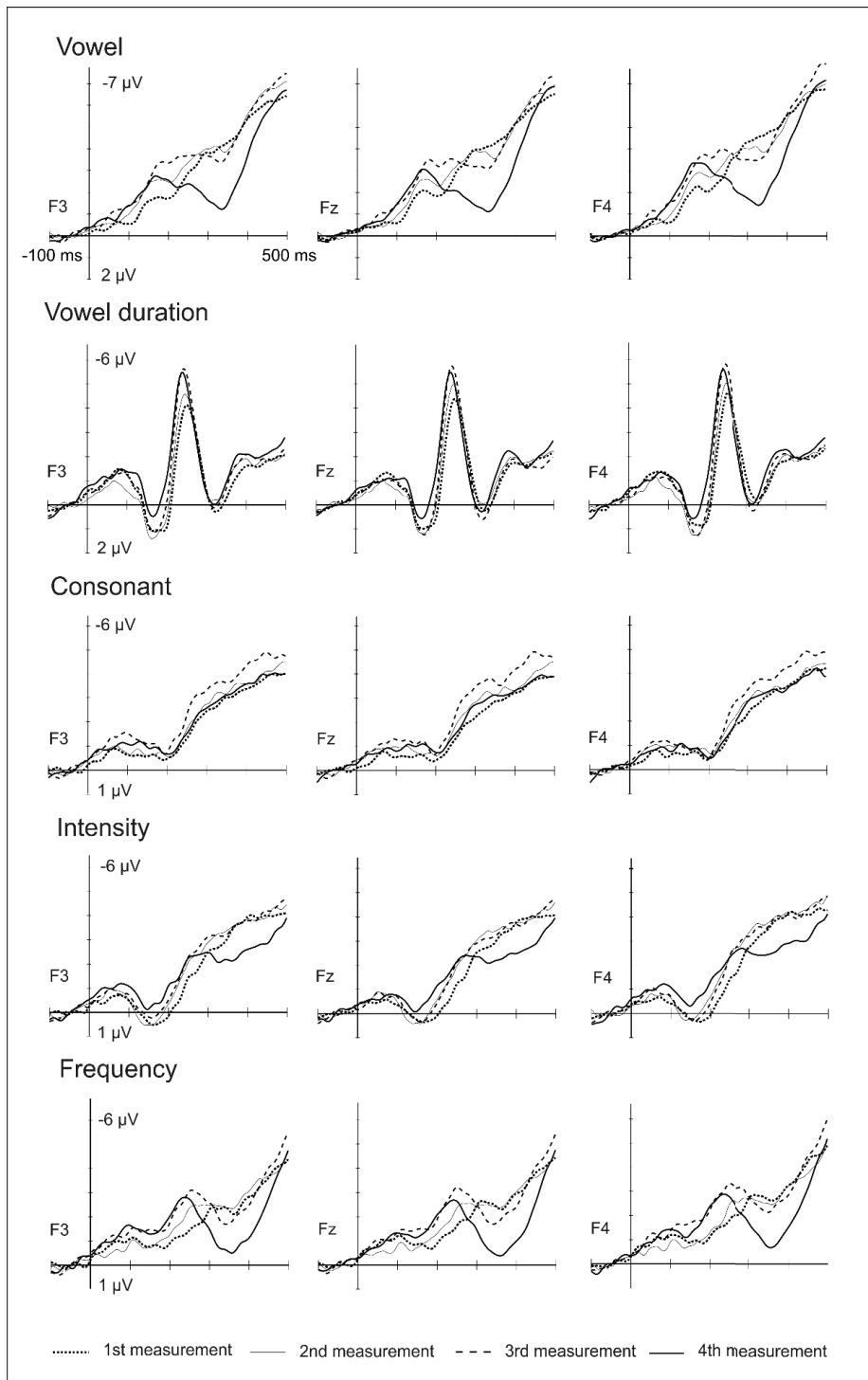
The standard responses for frontline electrodes (F3, Fz, F4) in all four measurements are depicted in the Figure 4 and the subtraction signals for frontline electrodes in Figure 5.

**Table 8** The MMN, P3a and LDN peak latencies in milliseconds from the stimulus onset for each deviant in each measurement. Please note that for the vowel duration deviant, the change occurs at 100 ms after stimulus onset. Separate time windows in study II were chosen based on the latencies of visible amplitude peaks and their theoretical fitness to children's response components.

Measurement		Latency (ms)			
		1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	4 <sup>th</sup>
<i>MMN</i>					
	VOW	173	173	177	164
	DUR	249	245	241	238
	CON	299	297	267	290
	INT	306	297	257	242
	FRE	273	267	249	242
<i>P3a</i>					
	VOW	339	345	327	329
	DUR	323	319	319	319
	CON	361	351	361	363
	INT	333	339	335	329
	FRE	361	357	339	357
<i>LDN</i>					
	VOW	473	457	473	473
	DUR	397	393	397	385
	CON	473	461	447	467
	INT	473	469	473	473
	FRE	473	439	473	473



**Figure 4** Standard responses on frontline electrodes for all four measurements (Study II).



**Figure 5** Subtraction signals on frontline for all four measurements for all stimuli (Study II).

#### **4.2.1. The maturation of neural speech-sound discrimination (Study II) and the development of cognitive skills (Study III)**

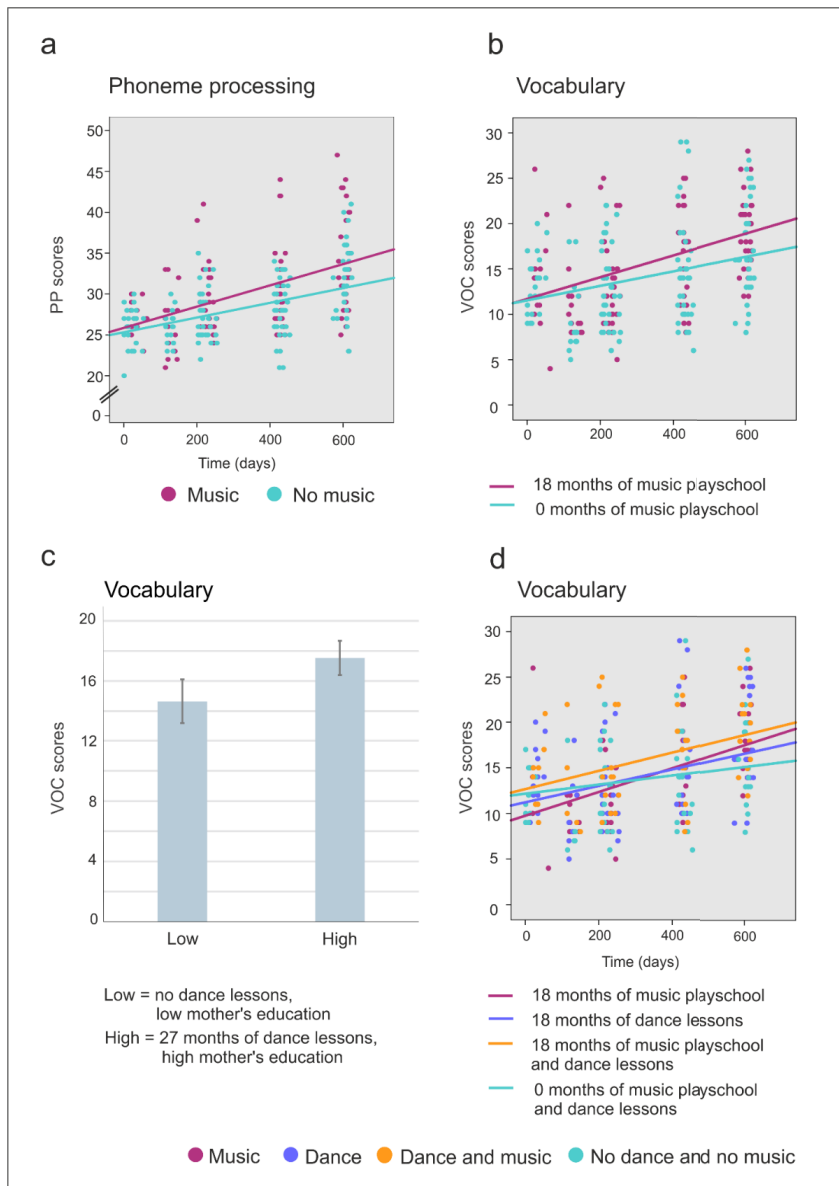
For MMN responses, the main effect of age was significant on the front line electrodes for *vowel deviant* [ $F(1, 191)=9.810, p=.002$ , parameter estimate  $-.052988$ ], *vowel duration deviant* [ $F(1,198)=11.337, p=.001$ , parameter estimate  $-.059168$ ] and *frequency deviant* [ $F(1, 189)=5.285, p=.023$ , parameter estimate  $-.034871$ ], showing that the MMN amplitudes increased with time. For P3a responses, the main effect of age was significant on the front line electrodes for *vowel deviant* [ $F(1, 214)=46.864, p<.001$ , parameter estimate  $.140570$ ], *intensity deviant* [ $F(1, 210)= 4.692, p=.031$ , parameter estimate  $.037629$ ] and *frequency deviant* [ $F(1, 209)=24.889, p<.001$ , parameter estimate  $.089703$ ], showing a decrease in amplitude in inspected time window. Furthermore, the main effect of age for LDN was significant on averaged deviants over nine electrodes for *intensity deviant* [ $F(1, 201)=8.220, p=.005$ , parameter estimate  $.042873$ ] and marginally significant for *vowel deviant* [ $F(1, 195)=3.701, p=.056$ , parameter estimate  $.033238$ ], showing a decrease in LDN responses with age.

The main effects of time were significant for all inspected neurocognitive tests, namely *Phoneme processing*, *Vocabulary*, *Perceptual reasoning index* and *Inhibition* [ $F(1, 177)=142.00, p<.001$ , parameter estimate $=.011$ ;  $F(1, 176)=95.535, p<.001$ ; parameter estimate $=.010$ ;  $F(1, 176)=99.42, p<.001$ , parameter estimate $=.014$ ;  $F(1, 179)=9.10, p=.003$ , parameter estimate $=.002$ , respectively], indicating that all the test scores improved with time.

#### **4.2.2. Effects of music playschool on the development of test scores (Study III)**

The main effect of music playschool on *Phoneme processing* test was significant [ $F(1, 55)=8.121, p=.006$ , parameter estimate $=.095$ ]. Furthermore, the interaction between music playschool and time was significant for both *Phoneme processing* and *Vocabulary* test scores [ $F(1, 175)=8.55, p=.004$ , parameter estimate $=.0002$ ;  $F(1, 174)=7.30, p=.008$ , parameter estimate $=.0002$ , respectively]. This indicates that for those children who participated in music playschool, improvement in *Phoneme processing* and *Vocabulary* test scores was significantly higher than for children not participating in music playschool (see Figures 6a and 6b).





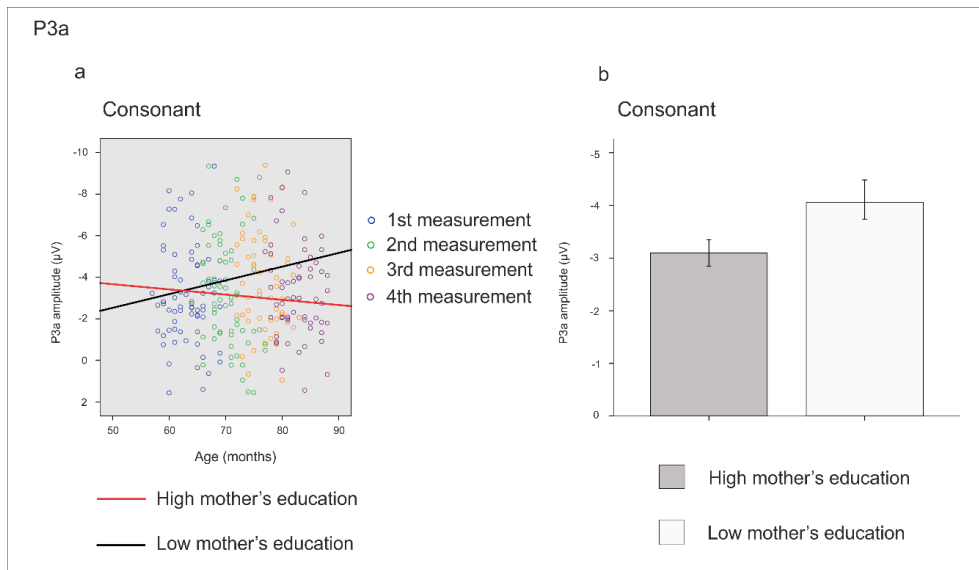
**Figure 6** Individual test scores for *Phoneme processing* and *Vocabulary* for all four test times. The lines in 6a) and 6b) represent the development of scores over time for children participating in music playschool either for 18 or 0 months (arbitrary cut-off-points chosen for illustration purposes) and in 6d) for children participating for 18 months either in music playschool or dance lessons, children participating in both activities for 18 months and children not participating in either activity. 6c) The bars represent the mean *Vocabulary* scores for children either not participating in dance lessons and having mother with low education (Low: scores 14.639,  $SEM=\pm 1.474$ ) or participating in dance lessons for 27 months and having mother with high education (High: scores 17.534,  $SEM=\pm 1.138$ ). Low mother's education stands for 2 and high for 6 on the scale of 1 to 7.

#### **4.2.3. Effects of maternal education on maturation of neural speech-sound discrimination (Study II)**

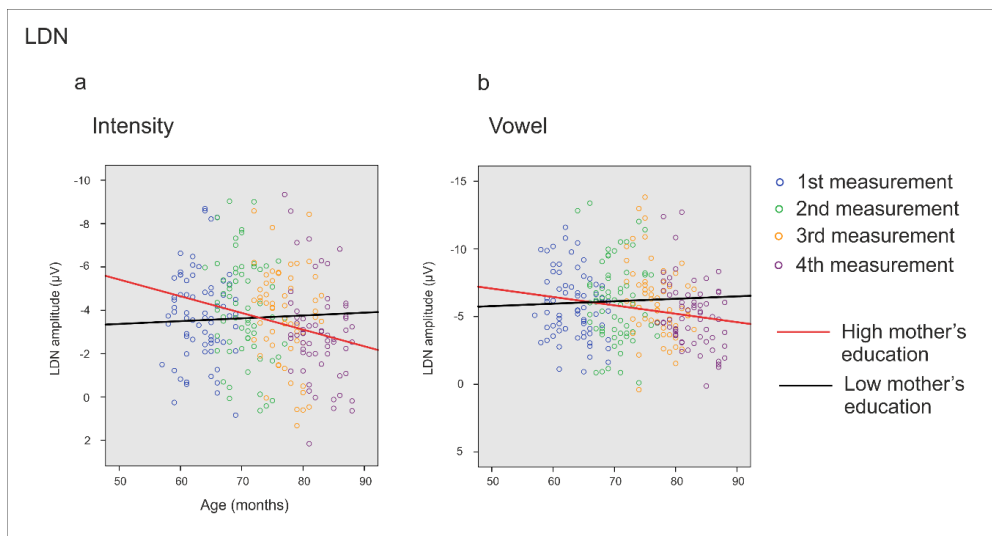
There was a significant interaction of age and mother's education on P3a component for *consonant deviant* [ $F(1, 206)= 3.937, p=.049$ , parameter estimate .022674] (Figure 7a) and further, a marginally significant main effect of mother's education on P3a was found for *consonant deviant* [ $F(1, 66)=3.167, p=.080$  parameter estimate .236972] (Figure 7b), indicating that the P3a responses of children with higher maternal education were shifting towards the positive polarity earlier than those of their peers with lower maternal education for this speech-sound feature. For the LDN response, the interaction of age and mother's education was significant for *intensity deviant* [ $F(1, 201)=4.839, p=.029$ , parameter estimate .021813] (Figure 8a) and marginally significant for *vowel deviant* [ $F(1, 195)=2.922, p=.089$ , parameter estimate .019586], indicating that these responses decreased more with age in children with higher maternal education (Figure 8b).

#### **4.2.4. Interactions between maternal education, dance lessons and music playschool contributing to the development of test scores (Study III)**

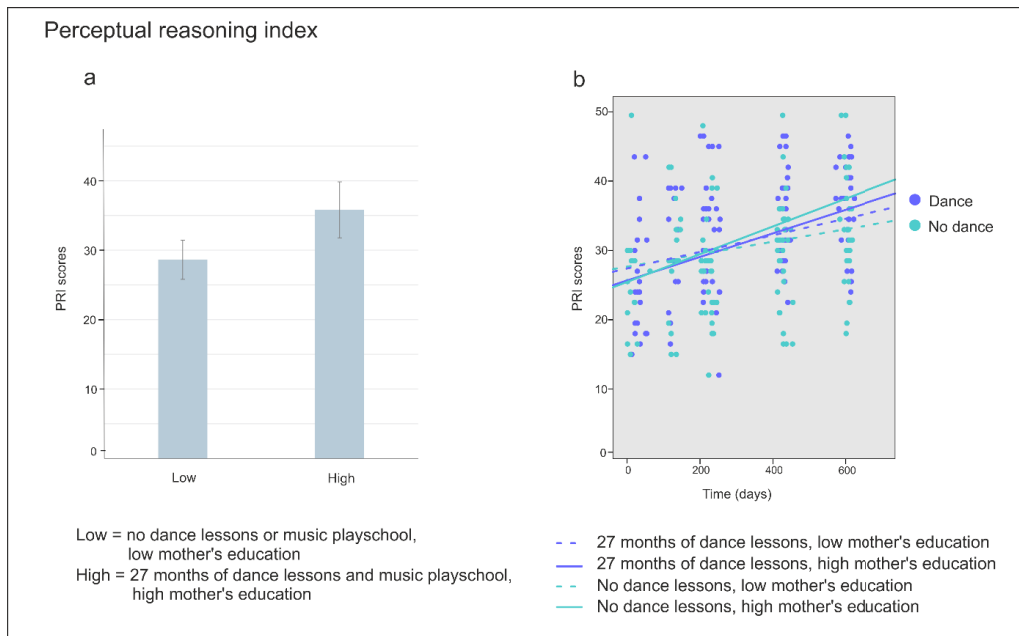
A significant interaction of mother's education and dance lessons on *Vocabulary* scores [ $F(1, 55)= 4.95, p=.030$ , parameter estimate=.061] indicated higher scores for children having a mother with higher education and participating in dance lessons (Figure 6c). Mother's education, music playschool and dance lessons had a significant three-way interaction on *Perceptual reasoning index* test scores [ $F(1, 56)=6.72, p=.012$ , parameter estimate=.009,] indicating that participating in music playschool and dance lessons and having a mother with higher education resulted higher *PRI* test scores (Figure 9a). In addition, the interaction between dance lessons, mother's education and time was significant on *Perceptual reasoning index* test scores [ $F(1, 175)=4.32, p=.039$ , parameter estimate .0001]. This interaction, however, is difficult to interpret (see Figure 9b).



**Figure 7** Significant interaction and marginally significant main effect for P3a response. The cut-off points for mother's education in figures are for illustration purposes only. 7a) Individual P3a amplitudes for *consonant deviants* for all four measurements. Red line represents change in amplitudes for an individual with high (6/7) and black line with low (2/7) maternal education. 7b) P3a amplitudes for *consonant deviant* averaged over all measurements for children with high (6/7) or low (2/7) maternal education (High: mean amplitude  $-3.10 \mu\text{V}$ ,  $\text{SEM} \pm 0.28$ , Low: mean amplitude  $-4.06 \mu\text{V}$ ,  $\text{SEM} \pm 0.40$ ).



**Figure 8** Significant and marginally significant interactions for LDN response. The cut-off points for mother's education in figures are for illustration purposes only. The red line represents change in amplitudes for an individual with high (6/7) and the black line for an individual with low (2/7) maternal education. 8a) Individual LDN amplitudes for *intensity deviant* for all four measurements. 8b) Individual LDN amplitudes for *vowel deviant* for all four measurements. Please note the different scales for the LDN response for *intensity* and *vowel deviations*.



**Figure 9** Mean and individual scores for *Perceptual reasoning index*. 9a) The bars represent the mean *Perceptual reasoning index* scores for children either not participating in dance lessons and having mother with low education (Low: scores 28.626,  $SEM=\pm 2.823$ ) or participating in dance lessons for 27 months and having mother with high education (High: scores 35.808,  $SEM=\pm 4.024$ ) (arbitrary cut-off-points chosen for illustration purposes). 9b) Individual test scores for all four test times. The lines represent the development of the scores for children participating in dance lessons for 27 or 0 months and having mother's with high or low education. Low mother's education stands for 2 and high for 6 on the scale of 1 to 7.

Finally, there was a significant interaction of music playschool, dance lessons and time on *Vocabulary* test scores [ $F(1, 175)=10.77, p=.001$ , parameter estimate= $-2.036 \times 10^{-5}$ ], indicating an extremely small decrease in scores with time (Figure 6d).

## 5. Discussion

The first aim of the thesis was to explore the maturation of neural speech-sound discrimination and its links to behavioral measures of language performance in children (Studies II and I). The second aim was to investigate the effects of music playschool on linguistic development of children (Study III).

There were three main findings of the thesis:

- The first main finding was that children's phoneme processing skills were associated with their neural auditory discrimination in the end of the first follow-up year when participants were 5–6-years old (Section 5.1).
- The second main finding was that during the inspected 20 months – and specifically during the second follow-up year – the auditory change detection reflected in the MMN, P3a and LDN responses to speech-sounds is still maturing, showing differential trajectories for different sound features and response components (Section 5.2).
- The third main finding was that music playschool enhanced children's linguistic skills (Section 5.3).

### 5.1. Links between neurocognitive tests and auditory ERPs

Based on Study I, children's phoneme processing skills are linked with their neural discrimination of speech-sounds at the age of 5 to 6. It seems that the automatic auditory discrimination reflects their ability of consciously processing phonological units. In the sample (N=70) the participants performing better in the *Phoneme processing* subtest of NEPSY II showed larger MMN amplitudes than their lower-scoring peers. This result suggests that in the early years of life, passive auditory change detection contributes to active linguistic skills, in this case phonological awareness. Instead, no association between the test and LDN responses were found. Present result does not show evidence for LDN being a response significantly reflecting linguistic processing, or at any rate being linked to the measured linguistic skills.

Furthermore, regarding the other linguistic test, *Auditory closure*, no connections to passively elicited auditory ERPs were found. Although ability to manipulate phoneme combinations is

without doubt required also in this test, AC may be more closely associated with vocabulary size and linguistic memory than with actual phonological awareness.

The mechanism behind the found association is not made explicit by the design of Study I. It could be that the accuracy of the auditory memory trace is reflected by neural discrimination: the more accurate the memory trace is, the more precise the neural discrimination, and the more effortless it is to consciously detect and manipulate the phonemes. The reason for differences in individual automatic change detection may lie in children's innate qualities or they may be a consequence of different auditory environments that children live in. In other words, it may be that children are genetically hardwired to develop differently in auditory discrimination, owing to, e.g., anatomical differences or the growth rate of myelination of the neurons. In addition to this, different auditory environments experienced in the childhood (e.g., noisy surroundings, music activities) together with genetic predisposition may affect the maturation of sound discrimination abilities. However, even though there is evidence for musically enriched environment's enhancing effect on neural speech-sound discrimination (Nan et al., 2018; Kraus et al., 2014; Chobert et al., 2014; Francois et al., 2013), the present study did not find such effects.

Whereas the association between neural auditory change detection and behavioral linguistic skills has previously been found in group-level comparisons between typically developing children and clinical groups (e.g., Kujala, 2007; Lovio et al., 2010), the present study shows that the association is apparent also within the group of typically developing children. As phonological awareness has been shown to predict later literacy and reading skills in several studies (Kirby et al., 2003; Silvén et al., 2004; MacDonald & Cornwall, 1995; Savage et al., 2005) in the future, brain responses to phoneme changes may help us to find early on children in need of interventions supporting their linguistic development. However, in addition to being noisy, the variation in children's individual event-related responses is large and thus, major advantages in both our knowledge of the typical maturation of ERPs and signal analyses need to take place before this is feasible at individual level.

The present study did not find any associations between children's neural speech-sound discrimination and non-verbal reasoning skills. This indicates that perceptual reasoning skills are not linked with the accuracy of auditory memory trace. Other studies finding associations between intelligence measures and neurophysiological indices of auditory discrimination

(Light et al., 2007; Partanen et al., 2013c; Mikkola et al., 2007; Liu et al., 2007; Salisbury, Polizzotto, Nestor, Haigh, Koehler & McCarley, 2017) vary extensively in their experimental settings, and it is thus difficult to draw any all-encompassing conclusions from them. More specifically, prior paradigms measuring neural auditory detection have differed extensively from each other: links have been found between either detection of changes in sound duration (Light et al., 2007; Salisbury et al., 2017), intensity (Partanen et al., 2013a), frequency (Mikkola et al., 2007; Salisbury et al., 2017) or consonant (Liu et al., 2007) and overall level of functional status (Light et al., 2007), verbal intelligence (Partanen et al., 2013c; Mikkola et al., 2007), working memory and processing speed (Salisbury et al., 2017) or children's overall intelligence (Liu et al., 2007). Furthermore, the participants in different studies present a heterogeneous group, ranging from pre- and full-term infants (Mikkola et al., 2007) to adults with schizophrenia (Salisbury et al., 2017).

Despite of not finding any straightforward associations between children's auditory ERPs and non-verbal intelligence, an interaction between intelligence measures and hemispheric distribution of responses was observed. Children with better perceptual reasoning skills showed more evenly distributed responses compared to the children not performing as well in these tests: participants with lower scores showed a right-side dominance. This difference in the lateralization of responses may reflect, e.g., differences in maturation, but is not explicable by Study I. However, the previous research about the lateralization of responses in connection with intelligence in children is scarce and inconsistent. According to some studies, children performing worse in intelligent tests or being younger show dominance for MMN responses in left (Bauer et al., 2009) or left and central (Partanen et al., 2013a) scalp regions, or alternatively they show more evenly distributed responses compared to adolescents with more right-lateralization (Everts et al., 2009).

The lack of coherent results suggests that intelligence measures are not linked in any simplistic way to automatic auditory discrimination. Further studies with, e.g., auditory ERPs are needed to indicate if and how non-linguistic cognitive processing is manifested in neural functioning.

## 5.2. Maturation of neural speech-sound discrimination

The maturation of neural speech-sound discrimination has not been studied previously by means of auditory ERPs, with such large number of children in longitudinal settings. In the current study, the children were followed for 20 months during which they were measured four times with the paradigm including five deviants in parallel. In addition, the conducted analyses take into account the children's individual ages at the time of each measurement. Thus, unlike in most studies, each measurement point did not represent an average age of the participants, but the built model describes in more age-related manner the maturation of auditory change detection.

Excluding consonant change, responses to all the speech-sound features matured with age, suggesting that during the fifth and sixth years of life auditory discrimination is still gaining in accuracy. However, regarding the response components, the age-related changes diverged for different sound features. The automatic change detection – reflected by the MMN component – was enhanced for vowel, vowel duration and frequency deviants, while the orienting of attention – indicated by the magnitude of the P3a responses – matured for vowel, intensity and frequency deviants. Furthermore, the LDN responses decreased significantly with age for the intensity deviant and marginally for the vowel deviant. Thus, it seems that the discrimination of especially vowel change, but also of frequency and intensity changes is improving before school-age. The fact that the response for consonant deviant did not show any maturation effects suggests that the change in the voice onset time within the first tens of milliseconds does not become more salient for children during the ages of 5–6 years, at least when played in a fast multifeature paradigm. Actually, even adults measured with similar paradigm (Pakarinen et al., 2009) failed to display any prominent MMN – not to mention P3a – peaks for such consonant deviation, and this suggests that the consonant change is indeed hard to detect in a rapid sound stream.

Former studies have presented conflicting evidence on the maturation of pre-attentive auditory change detection reflected in MMN amplitudes, some research arguing that MMN amplitude increases with age (Lee et al., 2012; Bishop et al., 2011; Wetzel & Schröger, 2007b; Wetzel, 2006; Wetzel et al., 2011; Partanen et al., 2013b) and some displaying no maturational effects on the MMN amplitude (Shafer et al., 2010; 2000; Gomot et al., 2000; Bishop et al., 2010). The current study suggests that this component increases in amplitude with age, which suggests that



pre-attentive auditory change detection for speech-sounds is still gaining in accuracy in pre-school age, at least for some sound features. However, it is likely that the measured neural discrimination is at least partly dependent on the experimental settings. Additionally, the MMN component indicating this pre-attentive auditory change detection might show different maturational phases along childhood, and more longitudinal research is needed to discover the developmental trajectory of this response outside the studied age-range.

Instead of novel sounds, the multifeature paradigm included acoustically small stimulus changes, apparently not salient enough to attract pre-school children's attention, as reflected in the P3a responses that displayed mostly negative polarities. However, particularly during the second follow-up year the response shifted towards the positive polarity suggesting an enhancement in the orienting of attention for changes in vowel, intensity and frequency features. However, the orienting of attention for consonant and vowel duration deviants did not seem to enhance during the inspected 20 months. As already mentioned, consonant deviation appears to be relatively indistinguishable in a fast multifeature paradigm. Instead, the response for vowel duration deviant seems to be very robust early on, suggesting that duration is an extremely salient sound feature already for Finnish pre-schoolers. Since Finnish is a quantity language (both vowel and consonant durations contribute to the meaning of the word), this is not surprising as the ability to differentiate phoneme duration affects understanding of speech, and larger MMN responses of Finnish versus Russian and German speakers to phoneme duration have been shown in adults (Ylinen, Shestakova, Alku & Huotilainen, 2005; Tervaniemi et al., 2006). Alternatively, the cause for the early robustness of the response for vowel duration could be that the processing of duration does not require an analysis of sound frequency contents, but merely detecting whether there is a sound or not, suffices. However, even though the P3a response for vowel duration was comparatively adult-like in the current study, some maturation in the form of an increase in the amplitude is likely to happen in later childhood. In a study by Pakarinen et al. (2009) with an identical paradigm to the current one, distinct positive P3a components for vowel duration deviant were found in adults.

The majority of studies indicate that P3a component for novel sounds decreases (Wetzel et al., 2011; Määttä et al., 2005; Gumenyuk et al., 2004; Cykowicz et al., 1996; Wetzel & Schröger, 2007b) with age reflecting the attenuation of distractibility, compared to studies proposing its increase (Kihara et al., 2010; Cykowicz & Friedman, 1997). The evidence on the course of P3a component's maturation for subtle sound changes is more conflicting. Several studies have not

found any age-related differences (Wetzel & Schröger, 2007a; Wetzel & Schröger, 2007b; Čeponienė et al., 2004), while an age-related decrease has also been found (Wetzel et al., 2006). Some studies have not analysed the differences between age groups but displayed figures that – by visual inspection – point to an increase in P3a amplitudes with age (Horváth, Czigler, Birkás, Winkler, & Gervai, 2009; Gomot et al., 2000; Shafer et al., 2000). According to the present study, the P3a component for the small deviations is shifting from negativity towards positivity, possibly reflecting the speech-sound changes approaching or exceeding an attentional threshold in pre-school age. Unlike with novel sounds, it is unlikely that these deviations – at least in a multifeature paradigm – are very distracting. Thus, it could be interpreted that whereas the control of involuntary orienting attention for novel sounds becomes easier with age (P3a amplitude decreases), the detection of minor sound-feature changes enhances (P3a amplitude increases) with age, proposing that these neural functions show distinct maturational trajectories – at least within the studied age range.

The LDN component decreased significantly with age for the intensity deviant and marginally for the vowel deviant. Although this decrease concerns only responses for two speech-sound features, the present result is supported by previous evidence (Gumenyuk et al., 2001; 2004; Bishop et al., 2011; Hommet et al., 2009; Määttä et al., 2005) reporting larger amplitudes for younger children. This reduction of LDN amplitudes with age has been found both for novel sounds (Gumenyuk et al., 2001; 2004; Määttä et al., 2005) and phoneme changes (Hommet et al., 2009; Bishop et al., 2011) and together with the current results they do not support the suggestion that the LDN is linked specifically with language processing (Bishop et al., 2011; Korpilahti et al., 2001; Korpilahti et al., 1996; Kuuluvainen et al., 2016). Even if intensity deviation is thought to incorporate a linguistic meaning (in Finnish language, changes in intensity convey only information on word stress patterns and on the emotional connotations of the speaker), the maturation pattern of LDN for all linguistically relevant speech-sound changes would be expected to resemble each other if the response component was associated with language processing.

### **5.3. The effects of music on linguistic skills and neural speech-sound discrimination**

#### **5.3.1. Music playschool and linguistic skills**

As children in the current research grew older, their performance in all the inspected tests improved. In addition, weekly music playschool had a positive effect on language-related test performance, namely on phoneme processing skills and vocabulary knowledge. According to the parameter estimates, after the 20 month's follow-up the scores of children participating in music playschool for two school-years (equaling 18 months of music playschool) were 2.77 points higher for *Phoneme processing* and 2.25 points higher for *Vocabulary* tests than their peers' not attending to music playschool. This improvement – not seen in the children attending weekly dance lessons – became apparent during two- but not one-year follow-up. This result is in line with converging evidence from several studies (François et al., 2013; Roden et al., 2012; Slater, et al., 2014; Moritz et al., 2013; Rautenberg, 2015; Flaughnacco et al., 2015; Moreno et al., 2009; Degé & Schwarzer, 2011; Moreno et al., 2011) proposing that the more intensive the intervention, the sooner the possible transfer effects appear. Previous studies focusing on phonological awareness have reported faster transfer effects (Moritz et al., 2013; Degé & Schwarzer, 2011; Overly, 2003) of interventions offering daily music sessions. Thus, it seems possible that the regular participation in frequent musical activities is the key factor in obtaining these linguistic benefits in relatively short time.

The finding that dance lessons did not boost phoneme processing skills like music playschool did, offers a possibility to disentangle the reasons for the found enhancement. Dance lessons also include musical elements such as moving to the beat, listening to music and expressing its emotional content. Furthermore, both are also social acts. However, the one element in music playschool – missing in dance lessons – is the training of sound production, whether done by singing or with simple instruments. This active sound production rehearsal may improve the differentiating of the frequency contents of sounds thus improving phoneme processing skills, a suggestion supported by a recent finding (Patscheke, Degé & Schwarzer, 2018) proposing that pitch but not rhythmic training improves phonological awareness.

It is conceivable that singing is also the factor behind the improved performance in the *Vocabulary* test in children attending to music playschool. Songs introduce new words in a

reinforcing context, and these words together with the familiar ones are consolidated by repetition in the developing brain. However, Moreno et al. (2011) found that even training including primarily listening activities (e.g., rhythm, pitch, melody) enhanced vocabulary knowledge, and this result suggests that there is also some other link between vocabulary and listening skills, not yet fully understood.

In addition to intensity of the training, the differences in kindergarten and school curricula between cultures may explain why the duration of effective music intervention has been shorter in some previous studies (Moritz et al., 2013; Degé & Schwarzer, 2011; Overy, 2003; Moreno et al., 2011). In Finland most day-care is provided and supported by municipalities, with teachers having an academic degree. Music sessions are a part of kindergartens routines, although the realization of self-provided music sessions varies according to the skills and interests of the personnel. Thus, it might be that the benefits of an *additional* music playschool provided by professional music teachers is revealed only after longer interventions.

### **5.3.2. Music playschool and neural speech-sound discrimination**

No effects of music playschool or dance lessons were found on the maturation of children's neural speech-sound discrimination. Several studies have shown that music interventions improve the neural accuracy of auditory detection for lexical tone changes (Nan et al., 2018), phonemes (Kraus et al., 2014), vowel duration and consonant changes (Chobert et al., 2014), segmenting speech sounds (Francois et al., 2013) and processing foreign phonemes (Carpentier et al., 2016) and incongruous sentence endings (Moreno & Besson, 2006), but the present study did not find any such causal connection between music and passively elicited ERPs. The lack of evidence for this connection suggests that the neural changes associated with the development in linguistic skills are not pinpointed with the specific speech-sound changes in Study II – an explanation that is evident with vocabulary knowledge but needs some contemplation considering phoneme processing skills. Combining the results from Studies I, II and III, it might be that with younger children, performance in the *Phoneme processing* test relies on the abilities that are mostly dependent on the accuracy of neural speech-sound discrimination, and this explains the results in Study I. However, as children grow older, they are able to proceed in the test. In addition to phoneme awareness, succeeding in the subsequent

sections requires good auditory memory (lasting for several seconds instead of milliseconds), an ability not measured by the current fast multifeature paradigm but likely to benefit from music activities. This might explain why children attending to music playschool showed enhanced development in behavioral linguistic skills but not on passive neural speech-sound discrimination.

### **5.3.3. Music playschool and intelligence and inhibition measures**

No evidence for causal effects of music playschool on perceptual intelligence abilities was found in Study III. This contradicts the results from some previous studies finding such effects (Schellenberg, 2004; Kaviani et al., 2014; Bugos & Jacobs, 2012). The current study does not support the view that formerly revealed differences in intelligence between musician and non-musician (adults and) children are caused by music training but may instead reflect the differences in the socioeconomic and genetic background of the children. Indeed, some studies suggest that a common genetic factor influences both intelligence and aspects of musical aptitude (Mosing, Pedersen, Madison & Ullén, 2014; Madison, Forsman, Blom, Karabanov & Ullén, 2009).

Furthermore, in Study III, the development of inhibitory skills did not show differential trajectories for children participating in music playschool, dance lessons or neither of them. As the current study contradicts the findings from several studies claiming such effects (Moreno et al., 2011; Jaschke et al., 2018; Bugos & DeMarie, 2017) and supports the findings of other studies not reporting such effects (Nan et al., 2018; Janus et al., 2016), more research is needed in order to make solid conclusions on this matter.

The lack of associations between music and inhibitory control or intelligence in Study III confirms that the linguistic skills tested here are not mediated via these functions. In other words, the enhanced development of linguistic skills in children attending to music playschool is not strongly linked with more general cognitive skills. It further suggests that in the present study, children participating in music playschool did not differ from others in their intellectual capacities or their abilities of executive functions.

## 5.4. Other contributing factors on maturation

Socioeconomic status, represented here with maternal education level, did not have any profound effect on maturation of neural speech-sound discrimination and cognitive development. More specifically, SES did not affect the responses or test performance when averaged over all measurements, excluding a marginally significant main effect of mother's education on P3a component for consonant change.

However, regarding P3a and LDN components, mother's education contributed to maturation of P3a for consonant change and to maturation of LDN for intensity deviant and marginally also for vowel deviant. These results suggest that these components mature slightly faster for higher- than lower-SES children. The results connecting mother's education to the maturation of the P3a response indicate that the involuntary attentional orienting to subtle sound changes is more enhanced in higher-SES children. However, the estimated maturational slopes for P3a for consonant change in Figure 7a shows that the interpretation of these maturational differences for consonant change is indeed challenging: the response components of children with lower-SES do not approach the positive values but show the opposite trajectory and grow more negative with age. This may be due to many ongoing processes of ERP maturation, or simply differences in component latencies between low- and high-SES children not investigated in the analyses of Study II.

Mother's education combined with participation in dance lessons contributed to overall performance for *Vocabulary* test (Study III), proposing that children with higher SES and attending to dance lessons show better vocabulary knowledge. According to the model, the children with, e.g., 18 months of dance lessons and high mother's education (6/7) scored 1.66 points better than their peers with no dance lessons and low maternal education (2/7) in the middle of the follow-up. Instead, children who had experience in both music playschool and dance lessons seemed to get a disadvantage from these activities in their vocabulary development. However, the children with many extra-curricular activities performed well already in the beginning of the longitudinal study and the size of the effect was extremely small. Thus, a ceiling effect of a sort might explain this result, as the children attending only music playschool and having lower scores in the first measurements reached these better performing children by the end of the follow-up.

Regarding non-verbal intelligence, the results of Study III are not straightforward. The finding that children from more educated families and more extra-curricular activities do better in intelligence tests is not surprising (see Bradley & Corwyn, 2002). However, as seen in the slopes in Figure 9b the interpretation of this interaction is cumbersome, and not explicable by the present results. Furthermore, this result was apparent with dance lessons but not with music playschool, which further confuses the interpretation, although it could be explained by the slightly higher SES of dance children compared to other children in the study.

According to previous studies, the SES has a link to neural auditory ERPs (Skoe, Krizman & Kraus, 2013; Pakulak & Neville, 2010), as well as behavioural language processing (Fernald, Marchman & Weisleder, 2012). However, in the present studies the SES did not have a profound effect on the maturation of the responses in Study II or the development of neurocognitive skills in Study III, which could be explained by the sample of kindergarten children. Irrespective of the location, Finnish municipal kindergartens are of similar high quality with teachers having an academic degree. In addition, the kindergartens are low-cost (free for low-SES families), and this enables children with different socio-economic backgrounds to benefit similarly from early childhood education.

## **5.5. Limitations, strengths and future directions**

The variation in children's individual ERPs is large, and a lot of information is inevitably lost in averaging responses over fixed time window. This is true with most studies investigating ERPs in children, and in future, the individual variation should be taken into account when focusing on the neural maturation.

More specifically related to the current thesis, in the second year of the follow-up the children entered pre-school (starting properly at the age of six in Finland) and the contribution of the teaching of letter symbols on the development of neural speech-sound discrimination is not clear. Nevertheless, as the maturation of auditory change detection was apparent also for frequency and intensity deviants, it might be inferred that the gaining of accuracy in neural speech-sound discrimination during this pre-school year were not caused solely by learning. However, this issue still requires more investigation.

When comparing children with or without music training the ideal situation (from the standpoint of experimental design) would be to allocate children randomly – or semi-randomly – to different activities, e.g. music and painting. In the case of the present thesis, it was not possible, as the interventions were offered by music and dance institutions and participation was voluntary. However, as the music and dance groups were offered in separate kindergartens, and the control children went to kindergartens not offering either of these activities, families were not completely free to choose the activity.

Regarding longitudinal studies including interventions stretching for years, it is unrealistic to expect non-motivated participants and their families to commit to long interventions needed for studying learning. Furthermore, it is more likely for children with higher socio-economical background than for their lower-SES peers to have support for their music, dance, or other training if they are randomized into active training group. Thus, community-based samples in large-scale follow-up studies seem a well-founded choice, provided that essential background information of children is collected and included in the analyses.

The strengths of the present studies are also worth mentioning. First of all, long follow-up studies with such large number of participants and so few drop-outs are rare. Success with participation is undoubtedly due to arranging the measurements to take place in children's own kindergartens and not in laboratory premises. In consequence of thus minimizing the efforts of caregivers, this arrangement allowed participation of families with more heterogeneous backgrounds than what is typical, to participate in the longitudinal research. Furthermore, the parents were asked to fill a long questionnaire only in the beginning of the study and only answer shortly in the end of the both school years of the follow-up. In addition, during the follow-up, children obviously got used to the EEG measurements that occurred approximately every six months and were relatively relaxed in the measurements. Still, the measurements were not too often to evoke resistance among the participants.

Another obvious strength of the present thesis is the use of *linear growth curve model* in Studies II and III. This method increased the sophistication of especially Study II, as it enabled the use of individual ages of the participants (instead of four “fixed” measurement points). Thus, it was possible to build up a very accurate description of the maturation of speech-sound ERPs in 5- to 6-year-old children.



Regarding children's neural maturation and linguistic development, more longitudinal studies with large samples are needed. It is not known if the currently found benefits of music on linguistic skills remain till later childhood or adolescence or do other children catch up at some point. In addition, we need studies in individuals who have stopped participating in musical activities revealing if the occurred changes disappear after quitting music activity.

## **5.6. Summary and conclusions**

In pre-school children, neural speech-sound discrimination is linked to behavioral phoneme processing skills. This association was apparent in children before entering the final year of pre-school. According to the present thesis, within 5 to 6 years of age, the maturation of neural speech-sound discrimination – reflected by transformation of auditory ERPs – increases in accuracy for several speech sound features. In a sample of 75 children this maturation showed an enhancement at the age of six, a year before Finnish children enter comprehensive school. Regarding some speech-sound features, higher SES appears to enhance this maturation, but has no profound effect on them. Together with previous studies, the present thesis suggests that P3a reflecting orienting of attention shows distinct maturational trajectories for distracting novel sounds and more subtle deviations. Regarding LDN response, no evidence was found for its linguistic relevance.

According to the thesis, music playschool has a positive effect on the development of pre-school children's linguistic skills but not on their intelligence or executive functions. However, these beneficial effects were not manifested in neural speech-sound discrimination. In connection with the results from Study I, this highlights the complexity of the links between neural and behavioral measures of linguistic development.

Nevertheless, this thesis encourages to use feasible music interventions – such as low-cost music playschool – in order to support children's linguistic development. It also illuminates the typical neural maturation regarding speech-sound discrimination – knowledge that might be used in future to discover individuals benefiting from interventions enhancing linguistic skills.

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